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Final Report

AGGREGATE SURFACING DESIGN GUIDE

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16. Abstract

This report comprises a Surfacing Design Guide For Aggregate and Unsurfaced roads administered by the Forest Service. It is intended to be used in the design of aggregate-surfaced and earth roads for new construction and resurfacing. It is also intended for the road design/engineer at the district level, or road manager who has same knowledge of basic road design practices. A review of surfacing design concepts is included, with brief discussions on material characterization, traffic, environment, performance, reliability, and special consideration such as frost or geotextiles. Detailed examples are also provided.

The design algorithm selected was developed by the Corps of Engineers at the Waterways Experiment Station, and incorporates rut depth as the failure criterion. Other variables include tire pressure, aggregate thickness, material strengths, load and number of repetitions.

A companion computer program, known as the Surfacing Thickness Program (STP) is also included to assist in the structural design of aggregate-surfaced and earth roads. A user's guide for this program is provided and forms part of this guide.

17. Key Words

Low volume roads
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1.0 INTRODUCTION

In 1988, the U.S Forest Service reviewed the current direction regarding the design of aggregate and asphalt road surfacings and produced a "Surfacing Design Evaluation Report" for internal use and discussion.[1] Three key recommendations resulted from that report and they were:

1. Adopt the revised 1986 AASHTO Design Guide and the companion program (DNPS86/PC) for bituminous surfaced roads.

2. Develop a Surfacing Design Guide for aggregate and unsurfaced roads using existing technology.

3. Incorporate the concept of multiple user levels into the design process. The user levels imply differing levels of complexity of operation and variability of design.

This project was initiated to develop a guide and companion computer program to assist in the structural design of aggregate-surfaced and earth roads. A Forest Service Advisory Board consisting of representatives from several Forest Service Regions was appointed to provide technical guidance during the project. Initially, the project focused on the review of existing technology related to the structural design of aggregate surfaced roads. That review indicated that research efforts to develop relationships for designing aggregate surfaces are scarce.[2]

Several existing relationships were identified as potential candidates for this design guide; however, no clear choice for adoption was discovered and all design methods currently available had some serious limitations. After considerable review, a relationship developed by the Corps of Engineers in 1978[3] was jointly selected by the Advisory Board and the Consultant as the thickness design algorithm for inclusion into the Design Guide and Computer Program. This algorithm has little, if any, field experience in its use; however, this is also true for most of the design algorithms reviewed. The equation was developed by researchers at the Corps' Waterways Experiment Station through a review of previous field data. The intent during its development was to provide a relationship as a

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[1]USDA Forest Service, "Surfacing Design Evaluation Report," unpublished, June 1988.

[2]ARE Inc., "Aggregate Surfacing Design Guide and Computer Program--Synthesis Report," February 1989.

[3]Barber, V.C., E.C. Odom and R.W. Patrick, "The Deterioration and Reliability of Pavements," Technical Report S-78-8, U.S. Army Engineers Waterways Experiment Station, Vicksburg, Miss., July 1978.

starting point which could be then refined through field experiments and the performance of roads designed with this algorithm.

In spite of the above reservations, this design algorithm was selected for the following reasons:

1. The design algorithm contains most of the design factors that were most important to the Forest Service.

2. The equation appears to be stable with respect to the range of design inputs selected for use.

3. The algorithm was the most sensitive to changes in tire pressure. The thickness differences resulting from tire pressure variation were greatest for lower strength materials as was expected. The magnitudes were in the expected range as well.

4. The design algorithm provided significantly reduced thickness requirements than those from Chapter 50 for similar design inputs. This was consistent with the general perception that the Chapter 50 design method for aggregate surfaces was conservative.

The project team and Advisory Board would like to emphasize that the need for field studies to refine the design algorithm is still a <u>critical</u> item in the development of aggregate surfacing design techniques for use by the Forest Service. Focused small-scale field validation experiments are vital to the continued use and acceptance of any design method proposed as a result of this project.

In short, there was some disappointment with the current state of existing technology in this area; however, it is important to move forward with a design method that can be immediately implemented using existing technology and which includes the factors felt to be most important to the Forest Service. Continued monitoring and improvement of the method will be important to its eventual success. It is also important that designers recognize that during the initial phases of the implementation, designs must be done with considerable judgment and that performance of the resulting surfaces should be monitored. The experience gained through this process will be useful to help refine the design algorithm.

1.1 Objectives

This design guide is intended to be used in the design of aggregate-surfaced and earth roads for new construction and re-surfacing. Two levels of design are available to the user. A "Basic Guide" is provided for cases where limited field information is available, or where a "quick" solution is needed for estimation purposes. If a more detailed design, including the effect of different seasons or the incorporation of reliability levels are desired, an "Advanced Guide" is also provided. Concise and specific discussions of various surfacing considerations are included herein. The design algorithm is described and detailed examples are also included. A computer program that accompanies this is also included for use on the IBM-PC or other compatibles. A User's Guide for the program is also included in this design guide.

This design guide is intended for the road designer/engineer at the district level, or road manager who has some knowledge of basic road design practices. The computer program is user-friendly to assist those designers who are unfamiliar with the specifics of surfacing. Recommended defaults are provided in both the design guide as well as in the computer program to aid the designer. However, it should be emphasized that the philosophy used in the design of the computer program is to provide a tool to assist with the routine computational chores. The program will assist designers as different alternatives are evaluated. It is not intended to remove the engineer from the design process.

1.2 Scope

Specifically, only aggregate surfaced and earth roads are included for consideration. Aggregate-surfaced roads can be defined as an unpaved road that has an unbound aggregate material as the surface course. An earth road consists of the native soil with the top portion compacted so as to withstand traffic loads.

The design guide consists of six chapters as follows:

Chapter 2: Surfacing Design Background. This chapter is intended as a review of surfacing design concepts. Tables and guidelines are presented to assist the designer where this information may not be readily available. Items discussed include material characterization, traffic, environment, performance, reliability, and special considerations such as frost or geotextiles.

Chapter 3 presents the Basic Design Guide. The design algorithm is discussed and also the procedure for a quick design. Charts are presented so a manual solution is possible. Examples for both aggregate-surfaced and earth roads are provided.

Chapter 4 presents the Advanced Design Guide. Here, more complex situations such as the effects of different seasons and reliability are present. Detailed step-by-step procedures are described, together with examples.

Chapter 5 Economic Analysis. The principles of engineering economy are presented with discussions on the costs that must by considered in any economic analysis. Two methods are described; the Equivalent Uniform Annual Cost (EUAC) and the Net Present Worth (NPW). Examples to illustrate both methods are included.

Chapter 6 Computer User's Guide. This describes the operation of the companion computer program called the Surfacing Thickness Program - STP.

Finally, four appendices are included:

Appendix A:	Glossary of Terms
Appendix B:	Equivalency Factors
Appendix C:	Reliability Factors
Appendix D:	Design with Geotextiles

2.0 SURFACING DESIGN BACKGROUND

This chapter is intended to provide a brief discussion of the various factors that should be considered when designing the surfacing of an aggregate-surfaced or earth road. For those designers unfamiliar with surfacing design concepts, this chapter is intended to be a primer only. However, it may also be a useful reference for experienced designers. More detailed discussions of pavement design principles can be found in many excellent reference texts and handbooks. Two such sources of information are Yoder and Witczak[4] and the 1986 AASHTO Design Guide.[5]

Procedures and guidelines are also presented in this guide to aid the designer in selecting reasonable values for design and in making appropriate choices. Each section presents concepts with some general guidelines for use, and continues with a more detailed analysis of each element. It is expected that roads not requiring a more detailed analysis will only require the information presented in the first portion of each section.

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[4]Yoder, E.J. and M.W. Witczak, Principles of Pavement Design, 2nd Edition, John Wiley & Sons, Inc., 1975.

[5]American Association of State Highway and Transportation Officials, AASHTO Guide for Design of Pavement Structures, AASHTO, 444 N. Capitol Street N.W., Suite 225, Washington, DC, 1986.

2.1 Pavement Structure

Most natural soils are not strong enough to support traffic without excessive surface maintenance and vehicle operating costs. For this reason, a "surfacing structure" is placed over the native materials to help distribute the load stresses and provide a longer lasting surface. Typically this pavement structure is "...a combination of subbase, base course and surface course placed on a subgrade to support the traffic load and distributes it to the roadbed."[6] In a flexible pavement, the surface course is generally hot mix asphalt concrete. However, for aggregate-surfaced and earth roads, the surface course is aggregate and the in-place roadbed soil, respectively. Generally, the in-place roadbed soil would be compacted to a predefined level. Figure 1 illustrates the differences between a conventional asphalt concrete pavement, aggregate-surfaced and earth roads.

Briefly, the philosophy of surfacing design for roads is to obtain a surface course thickness sufficient to provide acceptable performance for the expected traffic over a particular length of time, given assumptions regarding the maintenance to be provided on the facility. Several elements need to be addressed in the thickness design for aggregate-surfaced and earth roads. The following sections describe these elements which include:

a. Materials Characterization
b. Traffic
c. Environment
d. Performance Criteria
e. Reliability levels
f. Maintenance
g. Construction Minimums
h. Special Considerations

[6]Ibid.

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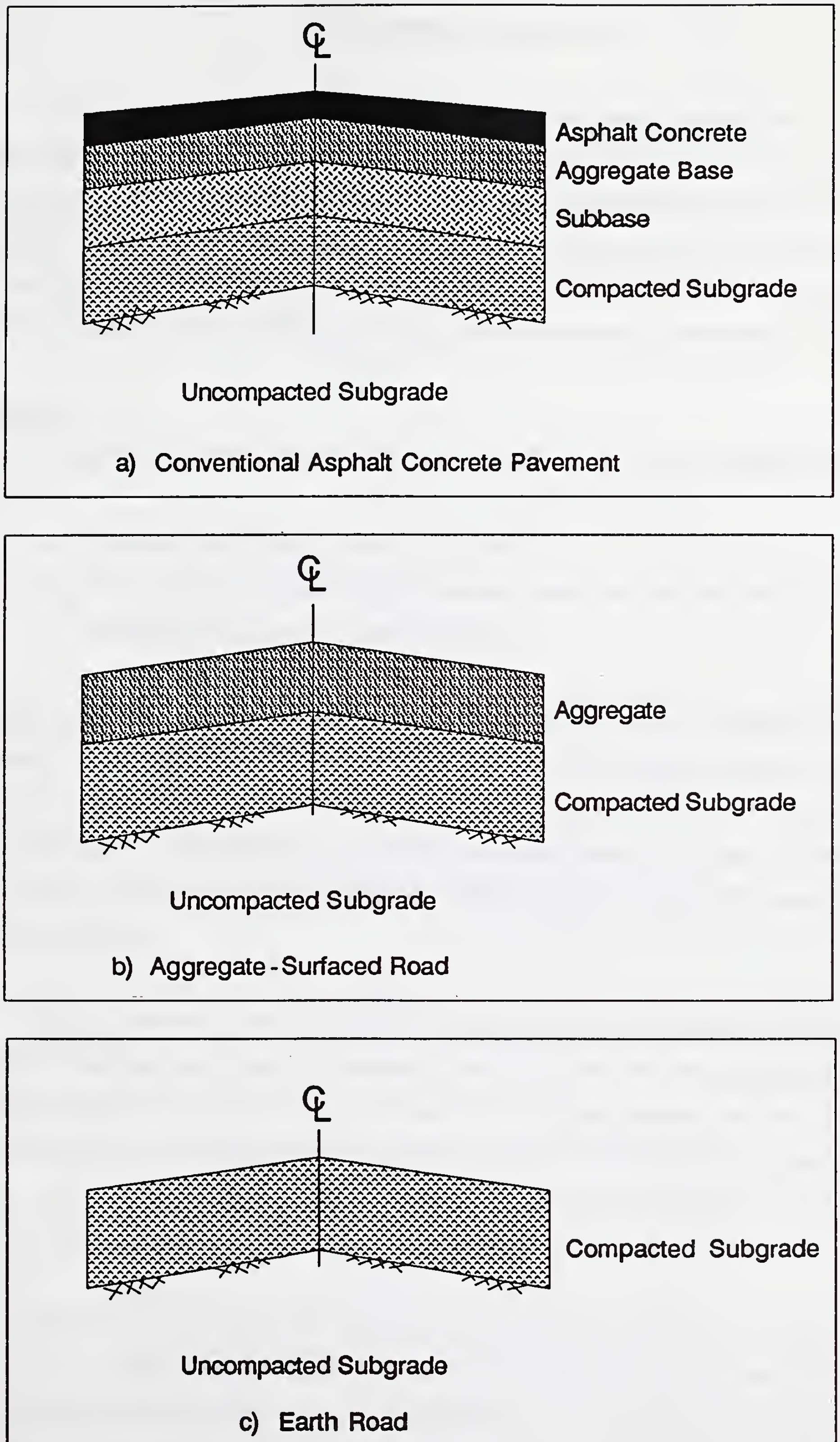


Figure 1. Typical Cross-Sections of Different Surface Types

2.2 Material Characterization

There are two material types that need to be considered in this guide; the native subgrade materials and the aggregate materials which comprise the surfacing layer. The discussion will first focus on the subgrade and then on aggregate materials. In both cases, some general concepts and guidelines are first presented for the designer. Information that is directed towards the more advanced user is also presented in the latter portion of this section. This section is intended to assist the designer in making decisions on the selection of material strength parameters for the program.

Subgrade Soils

Generally subgrade soils may be categorized into one of the following types:

- o Granular soils (best for road subgrades)
- o Fine-grained (or plastic) soils (variable quality for road subgrades)
- o Organic soils (poor for road subgrades)

Some general properties associated with different soil types are shown in Figure 2. Several systems are available to classify soil materials of which one of the most common is the Unified Soil Classification System. A flowchart for this classification system is shown in Figure 3 so the road designer may make initial classifications of the subgrade material. Figure 4 provides additional information with respect to the characteristics of different soils as classified under the Unified Soil Classification System.

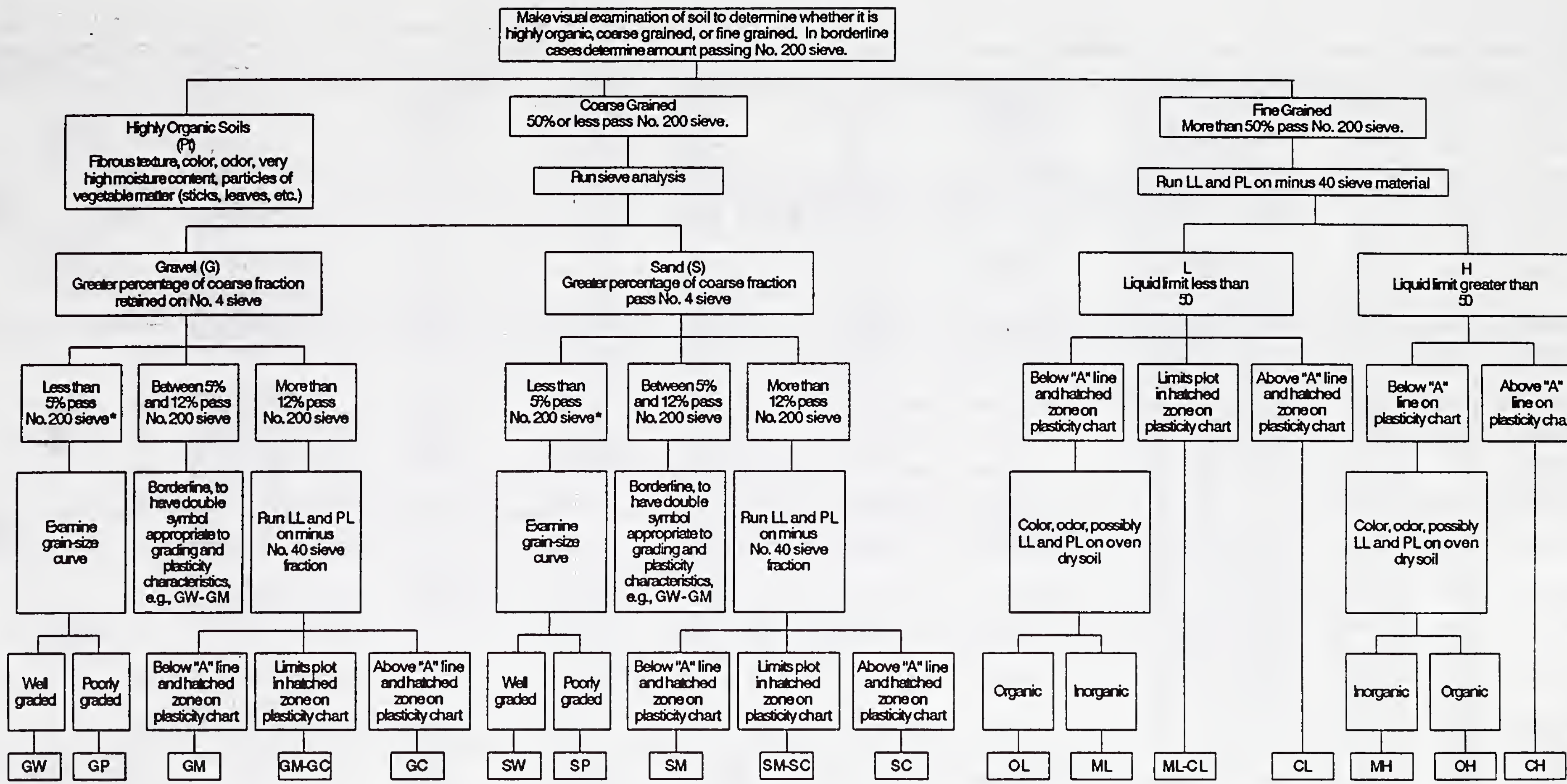
When designing roads, one of the most important characteristics of the subgrade soil is its strength. Generally, the higher the strength of the subgrade, the less aggregate will be required. For an earth road, this may result in more traffic or a longer season of use. Strength may be measured using the CBR (California Bearing Ratio), R-value (Soil Resistance value) or M_R (resilient modulus). An excellent subgrade can have a CBR approaching 80, while that of very soft materials can be 2 or less.

Several methods may be employed to determine the CBR of subgrade materials. The preferred method is to sample materials and perform laboratory testing and thus obtain values for use in the surfacing thickness program. If laboratory tests are not possible, the designer should look at past projects in the same area for historical CBR information. For example, Figure 5 presents a summary of historical laboratory-determined CBR data from the Willamette National Forest. Obviously

Figure 2. Properties associated with major soil types

Property	Granular soils	Fine-grained (or plastic) soils	Organic soils
Volume change with changes in water content	Little or none	Little to great shrinkage with drying, swell with wetting; may exert high swell pressure	Shrinks with drying; swells, but not with high swell pressure
Load-sustaining power	High, especially when confined or when containing fines	Low with soft or sensitive clay to high with firm or stiff clay	Low
Compression under static load	Little	High with soft clay to low with stiff or firm clay	Very high and difficult to control
Workability during prolonged wet periods	Good	Poor	Fair to poor
Ease of drainage	Easily drained	Difficult to drain	Often difficult to drain
Compactibility	Compacts to high density, especially with vibratory loads	Difficult to compact high density except under favorable conditions	Very difficult to compact; spongy

Source: Krebs, R.D. and Walker, R.D., Highway Materials, McGraw-Hill Book Company, 1971.



Note: Sieve sizes are U.S. Standard.
*If fines interfere with free-draining properties use double symbol such as GW-GM, etc.
Source: Federal Aviation Administration, "Airport Pavement Design and Evaluation", FAA Advisory Circular 150/5320-6C, 1978.

Figure 3. Flowchart for Unified Soil Classification System.

Figure 4. Characteristics pertinent to pavement foundations

Major Divisions (1)	(2)	Letter (3)	Name (4)	Value as Foundation When Not Subject to Frost Action (5)	Value as Base Directly under Wearing Surface (6)	Potential Frost Action (7)	Compressibility and Expansion (8)	Drainage Characteristics (9)	Compaction Equipment (10)	Unit Dry Weight (pcf) (11)	Field* CBR @ 100% of AASHTO T-180 (12)	Subgrade Modulus k (pci) (13)
Coarse grained soils	Gravel and gravelly soils	GW	Gravel or sandy gravel, well graded	Excellent	Good	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment, steel-wheeled roller	125-140	60-80	300 or more
		GP	Gravel or sandy gravel, poorly graded	Good to excellent	Poor to fair	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment, steel-wheeled roller	120-130	35-60	300 or more
		GU	Gravel or sandy gravel, uniformly graded	Good	Poor	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment	115-125	25-50	300 or more
		GM	Silty gravel or silty sandy gravel	Good to excellent	Fair to good	Slight to medium	Very slight	Fair to poor	Rubber-tired equipment, sheepsfoot roller, close control of moisture	130-145	40-80	300 or more
		GC	Clayey gravel or clayey sandy gravel	Good	Poor	Slight to medium	Slight	Poor to practically impervious	Rubber-tired equipment, sheepsfoot roller	120-140	20-40	200-300
	Sand and sandy soils	SW	Sand or gravelly sand, well graded	Good	Poor	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment,	110-130	20-40	200-300
		SP	Sand or gravelly sand, poorly graded	Fair to good	Poor to not suitable	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment	105-120	15-25	200-300
		SU	Sand or gravelly sand, uniformly graded	Fair to good	Not suitable	None to very slight	Almost none	Excellent	Crawler-type tractor, rubber-tired equipment	100-115	10-20	200-300
		SM	Silty sand or silty gravelly sand	Good	Poor	Slight to high	Very slight	Fair to poor	Rubber-tired equipment, sheepsfoot roller, close control of moisture	120-135	20-40	200-300
		SC	Clayey sand or clayey gravelly sand	Fair to good	Not suitable	Slight to high	Slight to medium	Poor to practically impervious	Rubber-tired equipment, sheepsfoot roller	105-130	10-20	200-300
Fine grained soils	Low compressibility LL < 50	ML	Silts, sandy silts, gravelly silts, or diatomaceous soils	Fair to poor	Not suitable	Medium to very high	Slight to medium	Fair to poor	Rubber-tired equipment, sheepsfoot roller, close control of moisture	100-125	5-15	100-200
		CL	Lean clays, sandy clays, or gravelly clays	Fair to poor	Not suitable	Medium to high	Medium	Practically impervious	Rubber-tired equipment, sheepsfoot roller	100-125	5-15	100-200
		OL	Organic silts or lean organic clays	Poor	Not suitable	Medium to High	Medium to high	Poor	Rubber-tired equipment, sheepsfoot roller	90-105	4-8	100-200
	High compressibility LL > 50	MH	Micaceous clays or diatomaceous soils	Poor	Not suitable	Medium to vary high	High	Fair to poor	Rubber-tired equipment, sheepsfoot roller	80-100	4-8	100-200
		CH	Fat clays	Poor to very poor	Not suitable	Medium	High	Practically impervious	Rubber-tired equipment, sheepsfoot roller	90-110	3-5	50-100
		OH	Fat organic clays	Poor to very poor	Not suitable	Medium	High	Practically impervious	Rubber-tired equipment, sheepsfoot roller	80-105	3-5	50-100
Peat & other fibrous organic soils		Pt	Peat, humus, and other	Not suitable	Not suitable	Slight	Very high	Fair to poor	Compaction not practical			

*To adjust CBRs to various compaction levels, use the relationships provided in Figure 6, Notes 1 to 3.

Source: Federal Aviation Administration, "Airport Pavement Design and Evaluation," FAA Advisory Circular 150/5320-6C, 1978.

Figure 5. Summary of historical laboratory CBR data from the Willamette National Forest

USCS Classification	CBR (% of T-99, soaked)			
	90%		95%	
	Range	Average	Range	Average
CH	1-4	2	2-5	3
CL	1-5	3	2-9	6
GC	–	6	–	13
GMd	1-16	5	5-54	14
GM-GC	–	1	–	8
GMu	1-22	5	2-40	11
GP	8-10	9	17-57	38
GP-GM	4-20	10	10-35	22
GW-GM	2-19	11	9-56	25
MH	1-8	3	1-14	6
ML	1-10	4	1-16	8
OL	–	2	–	5
SC	1-16	4	2-28	8
SMd	1-26	5	2-38	13
SM-SC	–	1	–	4
SMu	1-31	4	2-62	9
SP	–	9	–	11
SP-SM	1-9	5	13-19	16
SW-SM	1-17	8	3-31	14

Note: Data comes from Willamette NF and is site specific.

the data presented here is applicable only to the Willamette's roads. It is strongly recommended that individual forests perform field studies to evaluate simple tools, such as the dynamic cone penetrometer, for estimating subgrade strength. Also, each forest should develop a table similar to that shown in Figure 5 which summarizes historical CBR information.

For the user who wishes to perform a more advanced design, note that the compaction level and moisture conditions also affect the strength as measured by the CBR. Generally, the lower the level of compaction, or the higher the moisture content, the lower the strength. The effects of compaction are discussed in the following paragraphs while the effects of moisture are discussed in Section 2.5 as part of the environmental considerations.

Effects of Compaction on Design Value of CBR: For design purposes, it is necessary to utilize a CBR value which considers the variations in density and moisture which can be expected to occur during construction. The specifications may also allow densities less than those used by the laboratory in some standard test procedures. Since the CBR test procedure (AASHTO T 193) requires a plot of CBR vs density, the designer has information to evaluate the effect of compaction on the design CBR. It should be noted that in the standard CBR test (AASHTO T-193), the test is performed after a 96-hour soak. In order to simulate field moisture contents, it may be necessary to deviate from the test procedure and present the samples at "as-compacted" moisture contents.

When pavement structures consist of low quality, low cost aggregate surfaces, or when further information is not available, CBR values given in various engineering tables may be used. These values are generally for samples compacted to 100% of AASHTO T-99 or T-180. However, the required or expected compaction may be considerably less and adjustments are therefore necessary. CBR values generally vary in a predictable manner with compaction or density. Figure 6 presents some guidelines for the designer that may be useful. These relationships were derived from the Forest Service.[7] Note that Figures 4, 5 and 6 are all based on different assumptions; Figure 4 is based on 100% compaction (AASHTO T-180), Figure 5 is 90-95% compaction (AASHTO T-99), and Figure 6 is based on 85% compaction (T-99). This illustrates that the designer should obtain site-specific information if at all possible.

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[7]USDA Forest Service, "Interim Guide for Thickness Design of Flexible Pavement Structures", FSH 7709.11, Chapter 50, Region 6 Supplement No. 20, Portland, Oregon, January 1974.

Figure 6. Anticipated soil CBR range by USCS

Soil Classification	CBR Range[1]			
Cohesive Soils	85% T-99	90% T-99	95% T-99	100% T-99
GM_u	2.5 - 4	5 - 8	10 - 16	20 - 32
SM_u	1.0 - 2.5	2 - 5	4 - 10	8 - 20
ML	0.5 - 2.0	1 - 4	2 - 8	4 - 16
CL	0.5 - 2.0	1 - 4	2 - 8	4 - 16
OL	0.3 - 0.6	0.6-1.2	1.2-2.4	2.4-4.8
MH	0.5 - 2.0	1 - 4	2 - 8	4 - 16
CH	0.5 - 2.0	1 - 4	2 - 8	4 - 16
OH	0.3 - 0.6	0.6-1.2	1.2-2.4	2.4-4.8
Granular Soils				
GW	17 - 33	22 - 43	29 - 56	37 - 73
GP	13 - 25	17 - 33	22 - 42	29 - 55
SP	4 - 17	5 - 22	7 - 29	9 - 37
Intermediate Soils				
GM	8 - 12	14 - 20	23 - 35	39 - 59
GC	4 - 8	7 - 14	12 - 23	20 - 39
SM	3 - 8	5 - 14	9 - 23	15 - 39
SC	1 - 4	2 - 7	3 - 12	5 - 20

[1]The mean CBR value is taken as middle of the range. The standard deviation is taken as 1/4 of the range.

Notes: Other useful relationships are available:

1. Cohesive Soils - Multiply CBR values by 2.0 for each 5% increase in T-99 compaction above 85%. 95% of AASHTO T-180 maximum density is approximately equal to 100% of AASHTO T-99.

2. Granular and Base Soils - Multiply CBR values by 1.3 for each 5% increase in T-99 compaction above 85%. 97.5% of AASHTO T-180 is approximately equal to 100% of AASHTO T-99.

3. Intermediate soils - Multiply CBR values by 1.7 for each 5% increase in T-99 compaction above 85%.

Source: USDA Forest Service, "Interim guide for Thickness Design of Flexible Pavement Structures," FSH 7709.11, Chapter 50, Region 6 Supplement No. 20, Portland, OR, January 1974 (p.4, Table B) (Revised by USFS-R6, Jan. 1991).

The Forest Service has specifications that provide guidelines for the compaction that will be expected for different methods of construction (Forest Service Specifications [April-85] Section 203.15(b)). They are as follows:

Method 1.	Side Casting and End Dumping	80-85% AASHTO T-99
Method 2.	Layer Placement	85-90% AASHTO T-99
Method 3.	Layer Placement (Roller Compaction)	90-95% AASHTO T-99
Method 4.	Controlled Compaction	$\geq$ 95% AASHTO T-99
Method 5.	Controlled Compaction Using Density Control Strips	90-95% AASHTO T-99
Method 6.	Special Project Controlled Compaction	$\geq$ 95% AASHTO T-180 (for top foot) > 90% AASHTO T-180 (remaining layers)

<u>Aggregate Materials</u>

The strength of aggregate materials is generally dependent upon its:

- o Gradation
- o Durability or quality
- o Compaction
- o Subgrade strength

Laboratory determination of the CBR of aggregate materials is somewhat difficult because of the size of the aggregate. However, the strength in this surface layer is an important factor in determining the structural thicknesses required. If laboratory or historical data are unavailable, Figures 7, 8, and 9 may be used to provide guidelines regarding CBR values for use in the design algorithm. Figure 7 is reproduced from Chapter 50[8] and offers guidelines for the selection of an appropriate layer coefficient (a-value). The layer coefficient or a-value expresses the relative ability of a material to function as a structural component of the pavement. Figure 7 has some guidelines for suitable a-values to use for different aggregate materials, eg., 0.06 for cinders or 0.08 for fractured rock. Additional coefficients may be added if the material meets the criteria in the table. However, the presence of moisture can affect the relative strength of aggregate, hence the development of Figure 8. Moisture (m_i) values are suggested to modify the layer coefficients depending on the quality of drainage. Once an appropriate "a"-value has been selected, it can be correlated to a CBR based on the information in Figure 9.

Figure 10 demonstrates other criteria to target appropriate CBR values for the surfacing materials. The U.S. Army Corps of Engineers indicates that less expensive materials which are not as carefully

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[8]USDA Forest Service, "Interim Guide for Thickness Design of Flexible Pavement Structures". Op. Cit.

AGGREGATE BASE (a_2) AND SURFACING (a_1) (UNTREATED)

Use Base Coefficient 0.06 for Cinders; 0.07 for S & G; 0.08 for Fractured Rock

	PLASTICITY				GRADING			
					Pass 200		Pass 4	Pass 1.5"
	S.E.	P.I.						
Additional Coefficient	Base Only	Base	Surfacing	Quality	Base	Surfacing	Base and Surfacing	Base and Surfacing
+.01	> 35	< 6	2 - 9					
.00 .01 .02				Marginal Good Excellent				
.01					0 - 8	3 - 15		
.01							30 - 65	
.01								100

Note: 1. Coefficients based on compaction at 100% of AASHTO T 99.
2. Coefficients may be adjusted to other compaction levels by using the density and CBR relationships provided in Figure 6, Note 2.
3. Refer to Forest Service Specifications (April 85) Section 304.10 for relationships of compaction level versus percent of AASHTO T-99.

Source: USDA Forest Service, "Interim Guide for Thickness Design of Flexible Pavement Structures", FSH 7709.11, Chapter 50, Region 6 Supplement No. 20, Portland, Oregon, January 1974.

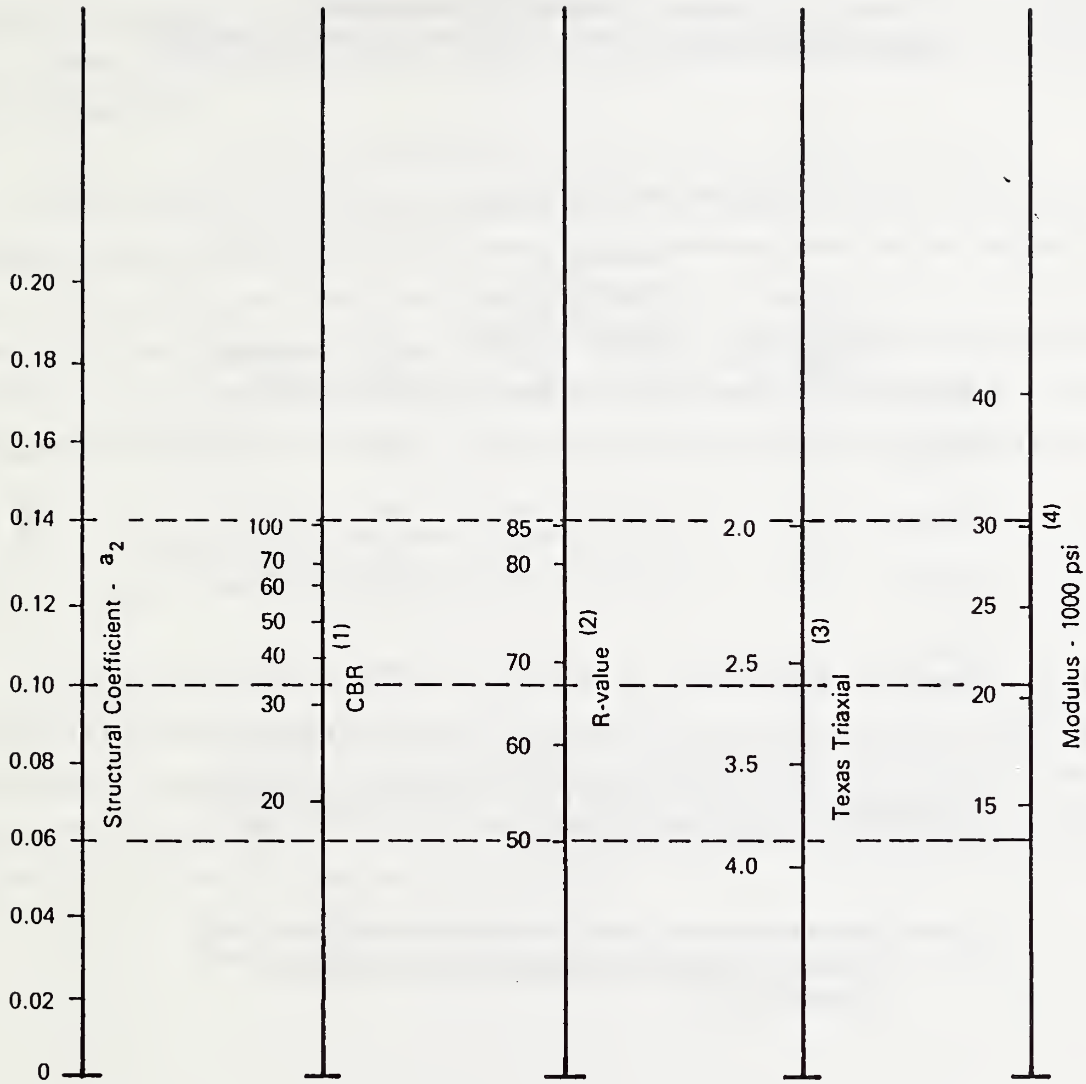
Figure 7. Guidelines for determining a-values for aggregate surfacing.

Figure 8. Recommended moisture (m_i) factors for modifying structural layer coefficients of untreated base and subbase materials in flexible pavements.

Quality of Drainage[1]	Percent of Time Pavement Structure is Exposed to Moisture Levels Approaching Saturation			
	Less than 1%	1-5%	5-25%	Greater than 25%
Excellent	1.40 - 1.35	1.35 - 1.30	1.30 - 1.20	1.20
Good	1.35 - 1.25	1.25 - 1.15	1.15 - 1.00	1.00
Fair	1.25 - 1.15	1.15 - 1.05	1.00 - 0.80	0.80
Poor	1.15 - 1.05	1.05 - 0.80	0.80 - 0.60	0.60
Very Poor	1.05 - 0.95	0.95 - 0.75	0.75 - 0.40	0.40

[1]The quality of drainage is expressed in terms of the time required to drain the base layer to 50% saturation. Excellent (2 hours), Good (1 day), Fair (7 days), Poor (1 month), Very Poor (does not drain).

Source: American Association of State Highway and Transportation Officials, AASHTO Guide for Design of Pavement Structures, 1986, Washington, D.C.



(1) Scale derived by averaging correlations obtained from Illinois. Specimens were molded using T-180.
(2) Scale derived by averaging correlations obtained from California, New Mexico and Wyoming.
(3) Scale derived by averaging correlations obtained from Texas.
(4) Scale derived on NCHRP project.

Figure 9. Correlations of a-values (a_2) with other strength measure recommended for crushed aggregate.

Source: American Association of State Highway and Transportation Officials, AASHTO Guide for Design of Pavement Structures, 1986, Washington, DC.

Figure 10. Example CBR Information
Maximum Permissible Values for Subbases and Select Materials.

Material	Maximum Design CBR	Size inch	Gradation Requirements Percent Passing No. 10 Sieve	Gradation Requirements Percent Passing No. 200 Sieve	Liquid Limit*	Plasticity Index*
Subbase	50	2	50	15	25	5
Subbase	40	2	80	15	25	5
Subbase	30	2	100	15	25	5
Select Material	20	3	--	--	35	12

*Determinations of these values will be made in accordance with ASTM D 4318 (AASHTO T-89 & T-90).

Source: Department of the Army, Technical Manual TM 5-822-3, Design of Aggregate Surfaced Roads and Airfields, Draft Version, 1988.

controlled do not warrant high CBR values. Maximum design CBR values are provided for materials which meet the criteria presented in the table. Figure 11 is a flowchart that illustrates the procedure for obtaining a design CBR.

Finally, it should be recognized that aggregate strength depends on subgrade strength. The development of the design algorithm was derived from data which indicated that, on average, the ratio of C_1 to C_2 is 4.4. Or in other words, the aggregate CBR is, on the average, 4.4 times greater than the subgrade CBR. Therefore, it is recommended that the CBR of the aggregate should not exceed 4 times the value of the subgrade CBR. If this ratio is not maintained, there is the possibility that the algorithm may no longer be applicable. For design, the aggregate CBR selected should be the lower of:

1. The procedure as illustrated in Figure 11.
2. Four times the subgrade CBR.

However, a lower limit of 20 is recommended for aggregate CBR. Typically, where weak subgrades are present, aggregate thicknesses may be such that more than 1 layer of differing strengths will be required. In such cases, an "effective" CBR (which may be greater than the 4:1 ratio) for all aggregate layers should be used in the program. Finally, there may be other reasons in selecting an aggregate, such as erosion or dust, rather than strength.

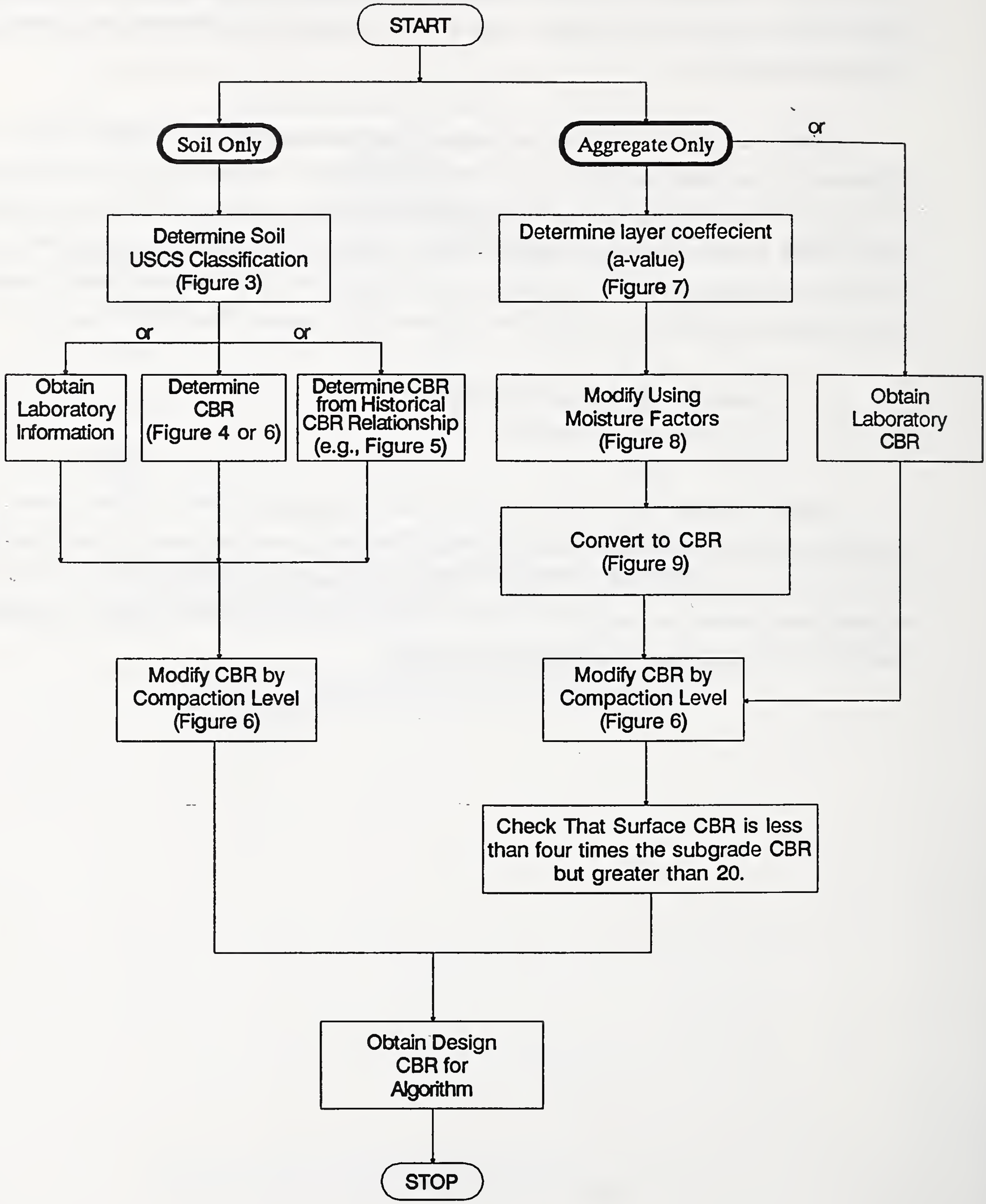


Figure 11. Flowchart to Determine Design CBRs.

2.3 Traffic

One of the most important factors to be evaluated in the structural design of any roadway is the effect of loads as transmitted by vehicles. The vehicle type, volume and mode of operation all affect the road design. Specifically, factors such as the tire and axle loads, load configuration and tire pressures are important.

Most design procedures employed in the U.S. for highway pavements employ a standard axle type and normally express pavement thickness as a function of the number of passes of the standard axle. In this design guide, the 18-kip equivalent single axle load (ESAL) with a tire pressure of 80 psi has been selected as the standard axle type. This is compatible with the design procedures of many state and federal agencies in the United States and, in fact, was the primary reason for its selection. The equivalent damage effects of all other vehicle types in terms of ESALs can then be determined.

Figures 12, 13, 14, 15 and 16 summarize the equivalency factors for various axle loads and configurations. The figures are for tire pressures of 25, 50, 70, 80 and 100 psi respectively. Appendix B describes the procedure to calculate these equivalencies if vehicles with unusual axle loads are present. Therefore, a standard log truck with 2 tandem axles of 35 kips each, a steering axle of 10 kips, (single axle, single wheel) all at a tire pressure of 80 psi (see Figure 14) would have an equivalency factor of:

$$2(1.36) + 0.45 = 3.17$$

Each vehicle type, as shown above, has its own Equivalent Single Wheel Load (ESWL) or equivalency factor. This factor is a function of the number and type of axles, load and tire pressure. Chapters 3 and 4 contain examples in using these equivalency factors for design.

In addition, Figure 17 has been included at the request of the Advisory Board for trucks with triple axles. This figure is from the AASHTO guide and the equivalencies were developed for flexible pavements and a terminal serviceability index of 2.0. The Corps of Engineers did not develop any curves for triple axle trucks.

Figure 12. Equivalency Factors for tire pressures of 25 psi

Single Axle Single Wheel (kips)	Equivalency Factor	Tandem Axle Dual Wheels (kips)	Equivalency Factor	Tandem Axle Dual Wheels (kips)	Equivalency Factor	Tandem Axle Dual Wheels (kips)	Equivalency Factor
2	0.00	10	0.01	50	0.18	90	0.56
4	0.01	11	0.01	51	0.19	91	0.57
6	0.01	12	0.01	52	0.20	92	0.59
8	0.02	13	0.01	53	0.21	93	0.60
10	0.03	14	0.02	54	0.21	94	0.61
12	0.04	15	0.02	55	0.22	95	0.62
14	0.06	16	0.02	56	0.23	96	0.64
16	0.08	17	0.02	57	0.24	97	0.65
18	0.10	18	0.03	58	0.24	98	0.66
20	0.12	19	0.03	59	0.25	99	0.67
22	0.14	20	0.03	60	0.26	100	0.69
24	0.16	21	0.04	61	0.27	101	0.70
26	0.19	22	0.04	62	0.28	102	0.71
28	0.22	23	0.04	63	0.29	103	0.73
30	0.25	24	0.05	64	0.29	104	0.74
32	0.28	25	0.05	65	0.30	105	0.75
34	0.32	26	0.05	66	0.31	106	0.77
36	0.36	27	0.06	67	0.32	107	0.78
38	0.39	28	0.06	68	0.33	108	0.80
40	0.44	29	0.07	69	0.34	109	0.81
Single Axle Dual Wheels (kips)	Equivalency Factor	30	0.07	70	0.35	110	0.82
		31	0.07	71	0.36	111	0.84
		32	0.08	72	0.37	112	0.85
		33	0.08	73	0.38	113	0.87
		34	0.09	74	0.39	114	0.88
1	0.00	35	0.09	75	0.40	115	0.90
2	0.00	36	0.10	76	0.41	116	0.91
5	0.01	37	0.10	77	0.42	117	0.93
8	0.01	38	0.11	78	0.43	118	0.94
10	0.02	39	0.11	79	0.44	119	0.96
15	0.05	40	0.12	80	0.45	120	0.97
20	0.08	41	0.13	81	0.46	121	0.99
25	0.13	42	0.13	82	0.47	122	1.00
30	0.18	43	0.14	83	0.48	123	1.02
35	0.24	44	0.14	84	0.49	124	1.03
40	0.31	45	0.15	85	0.50	125	1.05
45	0.39	46	0.16	86	0.52	126	1.07
50	0.48	47	0.16	87	0.53	127	1.08
55	0.58	48	0.17	88	0.54	128	1.10
60	0.68	49	0.18	89	0.55	129	1.12

Figure 13. Equivalency Factors for tire pressures of 50 psi

Single Axle Single Wheel (kips)	Equivalency Factor	Tandem Axle Dual Wheels (kips)	Equivalency Factor	Tandem Axle Dual Wheels (kips)	Equivalency Factor	Tandem Axle Dual Wheels (kips)	Equivalency Factor
2	0.01	10	0.04	50	0.91	90	2.77
4	0.03	11	0.05	51	0.94	91	2.83
6	0.06	12	0.06	52	0.98	92	2.89
8	0.10	13	0.07	53	1.01	93	2.95
10	0.15	14	0.08	54	1.05	94	3.01
12	0.22	15	0.09	55	1.09	95	3.07
14	0.29	16	0.10	56	1.13	96	3.13
16	0.38	17	0.12	57	1.16	97	3.20
18	0.47	18	0.13	58	1.20	98	3.26
20	0.57	19	0.14	59	1.24	99	3.32
22	0.69	20	0.16	60	1.28	100	3.39
24	0.81	21	0.17	61	1.32	101	3.45
26	0.95	22	0.19	62	1.37	102	3.52
28	1.09	23	0.21	63	1.41	103	3.58
30	1.24	24	0.22	64	1.45	104	3.65
32	1.40	25	0.24	65	1.49	105	3.71
34	1.57	26	0.26	66	1.54	106	3.78
36	1.75	27	0.28	67	1.58	107	3.85
38	1.94	28	0.30	68	1.63	108	3.92
40	2.14	29	0.32	69	1.67	109	3.99
Single Axle Dual Wheels (kips)	Equivalency Factor	30	0.34	70	1.72	110	4.06
		31	0.37	71	1.77	111	4.13
		32	0.39	72	1.81	112	4.20
		33	0.41	73	1.86	113	4.27
		34	0.44	74	1.91	114	4.34
1	0.00	35	0.46	75	1.96	115	4.41
2	0.01	36	0.49	76	2.01	116	4.49
5	0.03	37	0.51	77	2.06	117	4.56
8	0.07	38	0.54	78	2.11	118	4.64
10	0.11	39	0.57	79	2.16	119	4.71
15	0.24	40	0.59	80	2.22	120	4.79
20	0.41	41	0.62	81	2.27	121	4.86
25	0.63	42	0.65	82	2.32	122	4.94
30	0.90	43	0.68	83	2.38	123	5.02
35	1.20	44	0.71	84	2.43	124	5.09
40	1.55	45	0.74	85	2.49	125	5.17
45	1.93	46	0.77	86	2.54	126	5.25
50	2.36	47	0.81	87	2.60	127	5.33
55	2.83	48	0.84	88	2.66	128	5.41
60	3.34	49	0.87	89	2.71	129	5.49

Figure 14. Equivalency Factors for tire pressures of 70 psi

Single Axle Single Wheel (kips)	Equivalency Factor
2	0.02
4	0.06
6	0.13
8	0.22
10	0.33
12	0.47
14	0.63
16	0.82
18	1.02
20	1.25
22	1.49
24	1.76
26	2.05
28	2.36
30	2.69
32	3.04
34	3.41
36	3.80
38	4.22
40	4.65

Single Axle Dual Wheels (kips)	Equivalency Factor
1	0.00
2	0.01
5	0.06
8	0.16
10	0.24
15	0.52
20	0.90
25	1.37
30	1.94
35	2.60
40	3.35
45	4.19
50	5.12
55	6.14
60	7.24

Tandem Axle Dual Wheels (kips)	Equivalency Factor	Tandem Axle Dual Wheels (kips)	Equivalency Factor	Tandem Axle Dual Wheels (kips)	Equivalency Factor
10	0.09	50	1.97	90	6.01
11	0.11	51	2.04	91	6.14
12	0.13	52	2.12	92	6.26
13	0.15	53	2.20	93	6.39
14	0.18	54	2.28	94	6.53
15	0.20	55	2.36	95	6.66
16	0.23	56	2.44	96	6.79
17	0.25	57	2.52	97	6.93
18	0.28	58	2.61	98	7.06
19	0.31	59	2.69	99	7.20
20	0.34	60	2.78	100	7.34
21	0.38	61	2.87	101	7.48
22	0.41	62	2.96	102	7.62
23	0.45	63	3.05	103	7.76
24	0.49	64	3.14	104	7.91
25	0.53	65	3.24	105	8.05
26	0.57	66	3.33	106	8.20
27	0.61	67	3.43	107	8.35
28	0.65	68	3.53	108	8.50
29	0.70	69	3.63	109	8.65
30	0.75	70	3.73	110	8.80
31	0.79	71	3.83	111	8.95
32	0.84	72	3.93	112	9.10
33	0.89	73	4.04	113	9.26
34	0.95	74	4.14	114	9.41
35	1.00	75	4.25	115	9.57
36	1.05	76	4.36	116	9.73
37	1.11	77	4.47	117	9.89
38	1.17	78	4.58	118	10.05
39	1.23	79	4.69	119	10.21
40	1.29	80	4.80	120	10.38
41	1.35	81	4.92	121	10.54
42	1.41	82	5.03	122	10.71
43	1.48	83	5.15	123	10.88
44	1.54	84	5.27	124	11.05
45	1.61	85	5.39	125	11.22
46	1.68	86	5.51	126	11.39
47	1.75	87	5.63	127	11.56
48	1.82	88	5.76	128	11.73
49	1.89	89	5.88	129	11.91

Figure 15. Equivalency Factors for tire pressures of 80 psi

Single Axle Single Wheel (kips)	Equivalency Factor
2	0.02
4	0.08
6	0.17
8	0.30
10	0.45
12	0.64
14	0.86
16	1.11
18	1.39
20	1.69
22	2.03
24	2.39
26	2.79
28	3.21
30	3.66
32	4.14
34	4.64
36	5.17
38	5.73
40	6.32

Single Axle Dual Wheels (kips)	Equivalency Factor
1	0.00
2	0.02
5	0.09
8	0.21
10	0.33
15	0.71
20	1.22
25	1.87
30	2.64
35	3.54
40	4.56
45	5.70
50	6.97
55	8.35
60	9.85

Tandem Axle Dual Wheels (kips)	Equivalency Factor	Tandem Axle Dual Wheels (kips)	Equivalency Factor	Tandem Axle Dual Wheels (kips)	Equivalency Factor
10	0.13	50	2.67	90	8.17
11	0.15	51	2.78	91	8.34
12	0.18	52	2.88	92	8.52
13	0.21	53	2.99	93	8.69
14	0.24	54	3.10	94	8.87
15	0.27	55	3.20	95	9.05
16	0.31	56	3.32	96	9.23
17	0.34	57	3.43	97	9.42
18	0.38	58	3.55	98	9.60
19	0.43	59	3.66	99	9.79
20	0.47	60	3.78	100	9.98
21	0.51	61	3.90	101	10.17
22	0.56	62	4.02	102	10.36
23	0.61	63	4.15	103	10.56
24	0.66	64	4.27	104	10.75
25	0.72	65	4.40	105	10.95
26	0.77	66	4.53	106	11.15
27	0.83	67	4.66	107	11.35
28	0.89	68	4.80	108	11.55
29	0.95	69	4.93	109	11.75
30	1.01	70	5.07	110	11.96
31	1.08	71	5.21	111	12.17
32	1.15	72	5.35	112	12.38
33	1.21	73	5.49	113	12.59
34	1.29	74	5.63	114	12.80
35	1.36	75	5.78	115	13.01
36	1.43	76	5.92	116	13.23
37	1.51	77	6.07	117	13.45
38	1.59	78	6.22	118	13.67
39	1.67	79	6.38	119	13.89
40	1.75	80	6.53	120	14.11
41	1.83	81	6.69	121	14.33
42	1.92	82	6.84	122	14.56
43	2.01	83	7.00	123	14.79
44	2.10	84	7.17	124	15.02
45	2.19	85	7.33	125	15.25
46	2.28	86	7.49	126	15.48
47	2.38	87	7.66	127	15.71
48	2.47	88	7.83	128	15.95
49	2.57	89	8.00	129	16.19

Figure 16. Equivalency Factors for tire pressures of 100 psi

Single Axle Single Wheel (kips)	Equivalency Factor	Tandem Axle Dual Wheels (kips)	Equivalency Factor	Tandem Axle Dual Wheels (kips)	Equivalency Factor	Tandem Axle Dual Wheels (kips)	Equivalency Factor
2	0.04	10	0.21	50	4.47	90	13.65
4	0.13	11	0.25	51	4.64	91	13.94
6	0.29	12	0.30	52	4.81	92	14.23
8	0.50	13	0.35	53	4.99	93	14.53
10	0.76	14	0.40	54	5.17	94	14.82
12	1.07	15	0.45	55	5.35	95	15.12
14	1.44	16	0.51	56	5.54	96	15.43
16	1.85	17	0.58	57	5.73	97	15.73
18	2.32	18	0.64	58	5.92	98	16.04
20	2.83	19	0.71	59	6.12	99	16.36
22	3.39	20	0.78	60	6.32	100	16.67
24	4.00	21	0.86	61	6.52	101	16.99
26	4.66	22	0.94	62	6.72	102	17.31
28	5.36	23	1.02	63	6.93	103	17.64
30	6.11	24	1.11	64	7.14	104	17.96
32	6.91	25	1.20	65	7.35	105	18.29
34	7.75	26	1.29	66	7.57	106	18.62
36	8.64	27	1.39	67	7.79	107	18.96
38	9.58	28	1.48	68	8.01	108	19.30
40	10.56	29	1.59	69	8.24	109	19.64
Single Axle Dual Wheels (kips)	**Equivalency Factor**	30	1.69	70	8.47	110	19.98
		31	1.80	71	8.70	111	20.33
		32	1.91	72	8.93	112	20.68
		33	2.03	73	9.17	113	21.03
		34	2.15	74	9.41	114	21.38
1	0.01	35	2.27	75	9.65	115	21.74
2	0.03	36	2.39	76	9.90	116	22.10
5	0.15	37	2.52	77	10.15	117	22.47
8	0.36	38	2.65	78	10.40	118	22.83
10	0.55	39	2.79	79	10.65	119	23.20
15	1.18	40	2.92	80	10.91	120	23.57
20	2.04	41	3.06	81	11.17	121	23.95
25	3.12	42	3.21	82	11.44	122	24.33
30	4.41	43	3.35	83	11.70	123	24.71
35	5.91	44	3.50	84	11.97	124	25.09
40	7.62	45	3.66	85	12.24	125	25.47
45	9.53	46	3.81	86	12.52	126	25.86
50	11.64	47	3.97	87	12.80	127	26.25
55	13.95	48	4.13	88	13.08	128	26.65
60	16.45	49	4.30	89	13.36	129	27.05

Figure 17. Axle load equivalency factors for flexible pavements, triple axles and Pt of 2.0

Axle Load	Pavement Structural Number					
(kips)	1	2	3	4	5	6
2	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
4	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
6	0.0004	0.0004	0.0003	0.0003	0.0003	0.0003
8	0.0009	0.0010	0.0009	0.0008	0.0007	0.0007
10	0.002	0.002	0.002	0.002	0.002	0.001
12	0.004	0.004	0.004	0.003	0.003	0.003
14	0.006	0.007	0.007	0.006	0.006	0.005
16	0.010	0.012	0.012	0.010	0.009	0.009
18	0.016	0.019	0.019	0.017	0.015	0.015
20	0.024	0.029	0.029	0.026	0.024	0.023
22	0.034	0.042	0.042	0.038	0.035	0.034
24	0.049	0.058	0.060	0.055	0.051	0.048
26	0.068	0.080	0.083	0.077	0.071	0.068
28	0.093	0.107	0.113	0.105	0.098	0.094
30	0.125	0.140	0.149	0.140	0.131	0.126
32	0.164	0.182	0.194	0.184	0.173	0.167
34	0.213	0.233	0.248	0.238	0.225	0.217
36	0.273	0.294	0.313	0.303	0.288	0.279
38	0.346	0.368	0.390	0.381	0.364	0.353
40	0.434	0.456	0.481	0.473	0.454	0.443
42	0.538	0.560	0.587	0.580	0.561	0.548
44	0.662	0.682	0.710	0.705	0.686	0.673
46	0.807	0.825	0.852	0.849	0.831	0.818
48	0.976	0.992	1.015	1.014	0.999	0.987
50	1.17	1.18	1.20	1.20	1.19	1.18
52	1.40	1.40	1.42	1.42	1.41	1.40
54	1.66	1.66	1.66	1.66	1.66	1.66
56	1.95	1.95	1.93	1.93	1.94	1.94
58	2.29	2.27	2.24	2.23	2.25	2.27
60	2.67	2.64	2.59	2.57	2.60	2.63
62	3.10	3.06	2.98	2.95	2.99	3.04
64	3.59	3.53	3.41	3.37	3.42	3.49
66	4.13	4.05	3.89	3.83	3.90	3.99
68	4.73	4.63	4.43	4.34	4.42	4.54
70	5.40	5.28	5.03	4.90	5.00	5.15
72	6.15	6.00	5.68	5.52	5.63	5.82
74	6.97	6.79	6.41	6.20	6.33	6.56
76	7.88	7.67	7.21	6.94	7.08	7.36
78	8.88	8.63	8.09	7.75	7.90	8.23
80	9.98	9.69	9.05	8.63	8.79	9.18
82	11.2	10.8	10.1	9.6	9.8	10.2
84	12.5	12.1	11.2	10.6	10.8	11.3
86	13.9	13.5	12.5	11.8	11.9	12.5
88	15.5	15.0	13.8	13.0	13.2	13.8
90	17.2	16.6	15.3	14.3	14.5	15.2

Source: American Association of State Highway and Transportation Officials, AASHTO Guide for Design of Pavement Structures, 1986, Washington, D.C.

2.4 Construction Minimums

When designing an aggregate-surfaced road, the Forest Service has suggested certain construction minimums. Briefly, the design aggregate thickness should be the greater of:

1. 4 inches;
2. twice the maximum particle size; or
3. the structural requirements plus the aggregate loss.

These guidelines were obtained from Chapter 50.[9] The Forest Service Advisory Board recommended the use of a 4-inch depth as a practical minimum for structural design with this design guide. Thicknesses less than 4 inches are often chosen for considerations other than structural; i.e., erosion control, traction, dust control, or armoring.

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[9]USDA Forest Service Handbook, Chapter 50, Region 6 Supplement No. 20, Portland, OR, January 1974.

2.5 Environmental Considerations

The two main environmental factors which influence the design of surfacings are frost action and rainfall. The design method presented in this guide assumes that traffic loads will be restricted during spring thaw. Frost considerations are not included. The information provided herein summarizes some factors to consider and directs the advanced designer to appropriate references for further information if design for frost conditions is required.

Frost: Much of this section is extracted from "Design Criteria for Aggregate-Surfaced Roads and Airfields".[10] The detrimental effects of frost action in aggregate-surfaced roads are manifested by nonuniform heave of pavements during the winter and by loss of strength of affected soils during the thaw period. Frost-related problems also include possible loss of compaction, development of permanent roughness, restriction of drainage by the frozen strata, and excessive maintenance requirements. The conditions necessary to cause frost problems are susceptible soil, temperature, and water, and they must be present simultaneously for significant ice segregation to occur in subgrade materials. Therefore, the cold-wet climates are likely to have the most serious problem with frost penetration.

The Corps of Engineers has conducted extensive research on the effects of frost penetration on pavement design and performance.[11] For frost design purposes, soils are divided into eight groups, based on percent of 0.02 mm grain size material (Figure 18). The first four groups are generally suitable for base materials, and any of the eight groups may be encountered as subgrade soils. The soils are listed in approximate order of decreasing bearing capacity during periods of thaw and increasing order of susceptibility to frost heave, although the low coefficients of permeability of most clays restrict their heaving propensity. More detailed descriptions of the frost-susceptible soils (F1, F2, F3, and F4) are presented in Figure 19.

The Corps of Engineers has developed a method for determining the thickness design of a pavement that has adequate resistance to distortion by frost heave and cracking and distortion under traffic loads as affected by seasonal variation in subgrade support. This procedure is called the reduced subgrade strength method. The procedures to determine the reduced subgrade moduli of

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[10] Chou, 1989, Op. Cit.

[11] Berg, R., and T. Johnson, 1983. "Revised Procedure for Pavement Design Under Seasonal Frost Conditions," SR 83-27, Cold Regions Research and Engineering Laboratory, Hanover, NH.

Figure 18. Frost design soil classification

Frost Group	Kind of Soil	Percentage Finer than 0.02 mm by Weight	Typical Soil Types Under Unified Soil Classification System
NFS*	Gravels Crushed stone Crushed rock	0-1.5	GW, GP
	Sands	0-3	SW, SP
PFS**	Gravels Crushed stone Crushed rock	1.5-3	GW, GP
	Sands	3-10	SW, SP
S1	Gravelly soils	3-6	GW, GP, GW-GM, GP-GM
S2	Sandy soils	3-6	SW, SP, SW-SM, SP-SM
F1	Gravelly soils	6 to 10	GM, GW-GM, GP-GM
F2	Gravelly soils	10 to 20	GM, GW-GM, GP-GM
	Sands	6 to 15	SM, SW-SM, SP-SM
F3	Gravelly soils	Over 20	GM, GC
	Sands, except very fine silty sands	Over 15	SM, SC
	Clays, PI > 12	--	CL, CH
F4	All silts	--	ML, MH
	Very fine silty sands	Over 15	SM
	Clays, PI < 12	--	Cl, CL-ML
	Varied clays and other fine-grained, banded sediments	--	CL and ML CL, ML, and SM CL, CH, and ML CL, CH, ML and SM

* Not frost-susceptible.

** Possibly frost-susceptible, but requires laboratory test to determine frost design soil classification.

Source: Chou, Y.T., "Design Criteria for Aggregate-Surfaced Roads and Airfields", Technical Report GL-89-5, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, 1989.

Figure 19. Descriptions of frost-susceptible subgrade soils.

Group	Description
F1	Gravelly soils containing between 3 and 10 percent finer than 0.02 mm by weight
F2	Gravelly soils containing between 10 and 20 percent finer than 0.02 mm by weight; sands containing between 3 and 15 percent finer than 0.02 mm by weight
F3	Gravelly soils containing more than 20 percent finer than 0.02 mm by weight; sands, except very fine silty sands, containing more than 15 percent finer than 0.02 mm by weight; clays with plasticity indexes of more than 12
F4	All silts and very fine silty sands containing more than 15 percent finer than 0.02 mm by weight; clays with plasticity indexes of less than 12; varied clays and other fine-grained banded sediments

Source: Chou, Y.T., "Design Criteria for Aggregate-Surfaced Roads and Airfields", Technical Report GL-89-5, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, 1989.

the aggregates and the subgrade soils can be obtained from CRREL (Berg and Johnson).[12] When the reduced subgrade strength method is used for F4 subgrade soils, unusually rigorous control of subgrade preparation will be required to ensure that the subgrade is reasonably uniform to prevent or minimize objectionable differential heaving.

Moisture: Moisture conditions in the subgrade can affect the subgrade strength. Procedures have been developed in an attempt to refine aggregate thickness requirements by designing for seasonal haul. Aggregate thicknesses can be reduced by diverting the majority of heavy traffic to drier seasons during the year. First, it is necessary to develop relationships to demonstrate the variation of percent saturation of the subgrade through the year and the variation of CBR with respect to percent saturation. Once this has been performed, it is then possible to use this information to modify subgrade strength conditions at various times of the year. To design a road given that seasonal effects are a factor, Miner's Hypothesis is required. This is also known as the "linear summation of cycle ratios cumulative damage hypothesis", and permits an estimation of the damage to be made. It is expressed as:

$$\sum_{i=1}^{x} \frac{n_i}{N_i} \leq 1$$

where:

n_i	=	Actual number of repetitions.
N_i	=	Allowable number of repetitions.
i	=	Number of seasons.

If the damage ratio is less than or equal to 1.0, this indicates that the road as designed is adequate. If the ratio exceeds 1.0, then a structurally stronger road is required. A more complete description of performing a design and considering seasonal effects is included in Chapters 3 and 4.

It is important to recognize that if this level of sophistication in the design is desired, laboratory determination of the subgrade strength values is strongly recommended. Correlations with soil type or information gathered from other forests is not recommended.

[12]Berg and Johnson, 1983, Op. Cit.

2.6 Performance Criteria

The performance of the roadway surface is the trend of serviceability with load applications and is dependent upon a variety of factors and can be measured in a variety of ways. For paved roads, performance is usually measured in terms of a pavement serviceability index. The road roughness is the major factor which determines the index value. For aggregate-surfaced and earth roads, rutting is used as the measure of serviceability and performance. In addition, an allowable rut depth is used as the failure criterion in this design guide and design algorithm. However, it is expected that routine maintenance will be performed throughout the life of the road.

Many factors can affect the performance of pavement with time. For aggregate-surfaced and earth roads, the amount and timing of road maintenance is an important factor in the overall use of the roadway and can be a factor in the structural design of the aggregate-surfaced road. Timely maintenance and proper management in the use of an aggregate-surfaced road can be a major factor in both minimizing the thickness required and extending the season of use. Timely maintenance of an earth road can also be a factor in extending the season of use and minimizing the amount of damage which occurs. However, due to the lack of information on the effects of maintenance on aggregate-surfaced and earth roads, it is difficult to quantify the relationships between maintenance and surfacing thickness. It is recommended that the USFS conduct research in this area in the future.

This design method makes no attempt to quantify the effects of road maintenance (both the amount and timing). However, Figure 20 has been included as a guideline for earth roads. For example, if the total rut is 4 inches, and blading is to occur when the ruts are 3 inches, then maintenance occurs at 75% of the anticipated rut. Based on Figure 20, this is expected when approximately 31% of the traffic has occurred. Therefore, approximately 3 bladings are required to carry 100% of the estimated traffic. Finally, the designer should bear in mind that the management of the road, both in terms of the use of the road and the maintenance anticipated, needs to be consistent from design to execution and that major changes from that anticipated during design may lead to failure of the design.

Failure Criterion: This design method utilizes rut depth as the failure criterion. After discussion with the Advisory Board, it was decided that the allowable rut depth for all traffic service levels should be 2 inches.

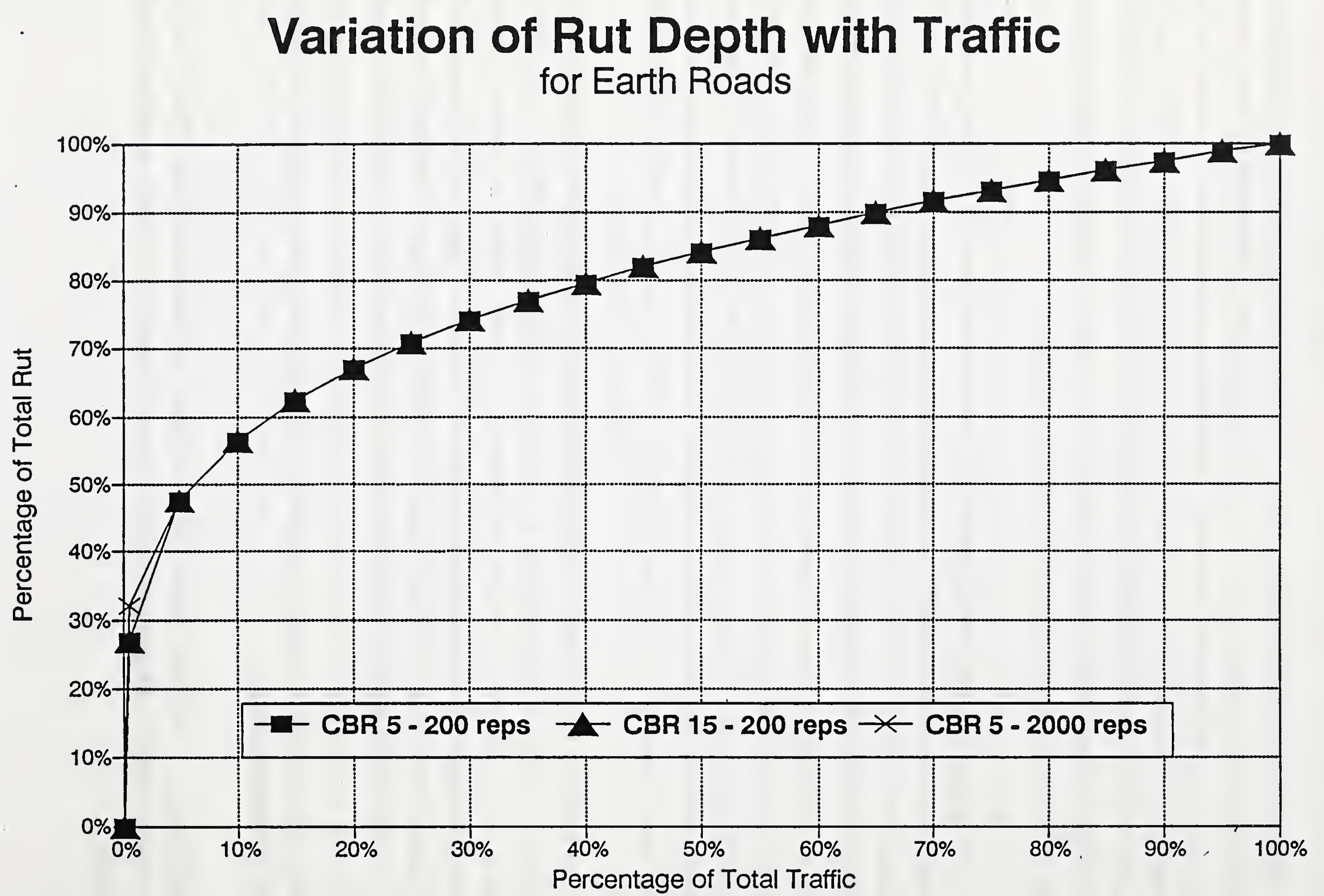

Figure 20. Variation of rut depth with traffic for earth roads

Operational Criteria: In addition to the aggregate necessary for supporting traffic loads, additional aggregate is required for maintenance which will be lost as the road is used. Computing this amount of aggregate loss is extremely difficult. It is recommended that aggregate loss be calculated using the following equation:

$$\text{Loss} = 0.12 + 0.1223\ (LT)$$

where: Loss = total aggregate loss, in inches, and

LT = number of loaded log trucks in thousands

Additionally, a more conservative rule of thumb of 1" per 10 MMBF may be used. Typically, 5000 BF is equivalent to 1 standard log truck. Therefore, the same rule may be expressed as 1" of aggregate loss for every 2,000 log trucks. If more specific local experience is available, it should be used instead of the relationships above. Additional relationships are available in the Synthesis Report.[13]

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[13] ARE Inc, "Aggregate Surfacing Design Guide and Computer Program", Dráft Synthesis Report, February 1989.

2.7 Reliability Levels

AASHTO describes the concept of reliability as follows:

> "The reliability of a pavement design performance process is the probability that a pavement section designed using the process will perform satisfactorily over the traffic and environmental conditions for the design period."

Briefly, a reliability design factor is used to increase the estimated traffic over the analysis period. Figure 21 provides some guidelines in the selection of an appropriate reliability factor. Generally, roads that are categorized as Traffic Service Level (TSL) D should have a 50% reliability; TSL C would be 70% and TSL B, 90%. These factors were determined using the equation developed by Barber et al. Appendix C describes in further detail the development of these factors. The variances and standard deviations used to arrive at these factors are also shown in this appendix. Only the aggregate-surfaced road design procedure incorporates the use of reliability levels.

Figure 21. Reliability Factors for Aggregate-Surfaced Roads.

Reliability Level %	Traffic Service Level	Reliability Factor F_R
50	D	1.0
70	C	1.44
90	B	2.32

Note: The default in the program is 50% reliability, which has F_R = 1.0.

Finally, the AASHTO Guide also states the following:

> "It is important to note that by treating design uncertainty as a separate factor, the designer should no longer use "conservative" estimates for all the other design input requirements. Rather than conservative values, the designer should use his best estimate of the mean or average value for each input value. The selected value of reliability and overall standard deviation will account for the combined effect of the variation of all the design variables."

2.8 Special Considerations

In addition to the frost considerations discussed previously in this chapter, the designer needs to be aware of other special problems which need to treated separately.

a. Design For Very Weak Subgrade (CBR < 3)

This design method is not appropriate for very weak subgrades. These very weak soils will typically be designed with geotextile subgrade reinforcement. Many design methods are in use today which provide design guidelines for designing soil-fabric-aggregate systems.[14,15] Appendix D contains a guide for design with geotextiles.

b. Use of Problem Materials

Problem materials may be defined in various ways; they may be materials that do not meet specifications, or they may perform satisfactorily in a dry condition but degrade under traffic in the presence of water or they may meet specifications but not perform as expected. Typically, problem materials have lower CBR values. It is advised that if problem materials are utilized, the CBR of the upper layer should be realistic. Guidelines for CBR's of aggregate materials have been provided previously in this chapter. Also, if it is expected that the material will degrade and produce excess fines, the gradation should be open to allow a nominal degradation of the material without adverse effect.

c. High Ground Water Table

If the local ground water table (for example, a spring) is expected to be within 3 feet of the subgrade surface during portions of the year, then provision should be made to either limit traffic or provide for positive drainage during those periods.

d. Control During Construction

While not necessarily a special problem, it should be emphasized that the assumptions made during design must be consistent with the construction and management of use of the aggregate-surfaced and earth facilities. Important items which must be carefully monitored during construction are:

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[14]Barenberg, Ernest J., "Design Procedures for Soil-Fabric-Aggregate Systems with Mirafi 500X", University of Illinois, Transportation Engineering Series No. 30

[15]Steward, J., R. Williamson and J. Mohney, "Guidelines for Use of Fabrics in Construction and Maintenance of Low-Volume Roads", U.S. Forest Service, June 1977, also FHWA Report FHWA-TS-78-205

1. Compaction of both subgrade and base
2. Depth, gradation and quality of aggregate

If the design has been performed assuming specific management policies will be followed with respect to use, and those policies are not followed, then the design will either be overly conservative and uneconomical or the road may not have sufficient aggregate thickness for the anticipated design life. The Forest Service has a guide available for reference, The Construction Materials Sampling & Testing Guide, EM 7720-5.

e. High Wheel Loads

Occasionally, there may be situations where very high wheel loads, eg. large yarders, may be allowed onto very soft subgrade, e.g., during the wet season. The design method does not analyze this situation and the involvement of the forest's geotechnical sections may be warranted. A bearing capacity solution may be more appropriate in these cases, or geotextiles may be required.

f. Low Tire Pressures

The use of Figures 12 through 16 will assist in the determination of the equivalency factors for vehicles with low tire pressures. One can interpolate between figures to obtain the corresponding equivalency factors.

g. Practical Range of Input Values.

Timber Volume:	0.5 to 100 MMBF (Note 1)
% Non-Log Truck Traffic:	0 to 100
Total 18k ESALs:	200 to 50,000 (Note 1)
Surface CBR (C1):	20 to 100
Subgrade CBR (C2):	3 to 30
C1/C2 Ratio:	1 to 4.4
Allowable rut depth:	Maximum of half the structural thickness

Note 1: The algorithm used for this program was based on a maximum of 50,000 total 18-kip ESALs. Traffic greater than this amount may have variables other than rutting dictating the structural thickness. These variables could be the timing and method of road maintenance, or the material properties of the aggregate.

3.0 BASIC DESIGN GUIDE

This chapter describes the design algorithm selected for the proposed USFS Surfacing Thickness Program (STP). Some background on the selection of this procedure is provided as well as example problems for a gravel-surfaced road and an earth road.

3.1 Design Algorithm

The algorithm selected for use in the STP was developed by the U.S. Army Corps of Engineers in 1978.[16] Existing rutting data at the Waterways Experiment Station for gravel-surfaced, earth and flexible pavements were utilized to develop deterioration and reliability models. A model was developed for aggregate-surfaced roads and this was selected for use by the Forest Service, as discussed in Chapter 1. The equation is shown below:

$$RD = 0.1741 \frac{P_k^{0.4704}\ t_p^{0.5695}\ R^{0.2476}}{(\log t)^{2.002}\ C_1^{0.9335}\ C_2^{0.2848}} \qquad \text{(Eqn. 3-1)}$$

where:

- RD = Rut depth, in.
- P_k = Equivalent single-wheel load (ESWL), kips
- t_p = Tire Pressure, psi
- t = Thickness of top layer, in.
- R = Repetitions of load or passes
- C_1 = CBR of top layer
- C_2 = CBR of subgrade layer

Since the standard axle is an 18-kip ESAL (ESWL = 8.64 kips from Appendix B) with tire pressures of 80 psi, Equation 3-1 may be further simplified to:

$$RD = 0.1741 \frac{(8.64^{k})^{0.4704}\ (80\ \text{psi})^{0.5695}\ R^{0.2476}}{(\log t)^{2.002}\ C_1^{0.9335}\ C_2^{0.2848}}$$

(Aggregate Roads Only) $$RD = 5.8230 \frac{R^{0.2476}}{(\log t)^{2.002}\ C_1^{0.9335}\ C_2^{0.2848}} \qquad \text{(Eqn. 3-2)}$$

[16]Barber, V.C., Op. Cit.

The rut depth is expressed as a function of load, tire pressure, number of passes or repetitions of axle loads, surface thickness and layer material strengths. Rut depth was selected as the failure criterion, and this is consistent with most other design procedures for aggregate-surfaced and earth roads.[17] Different combinations of aggregate layer thicknesses, soil strengths and number of passes may be used to calculate rut depths.

The same equation (3-1) is used for the design of earth-surfaced roads with one modification. Although an unsurfaced model was also developed by the Corps, it made the assumption that the top layer was actually weaker than the bottom layer. The rationale was that the upper portion may be adversely affected by moisture and organic materials in a military situation. However, for Forest Service conditions, it is expected that compaction from construction traffic and trucks would offset these effects. Therefore, that model was not selected. The modification to Equation 3-2 involves the assumption that the thickness (t) of an earth road is 6 inches. This is estimated to be the depth of compaction that would occur during construction. Therefore, the design algorithm may be further simplified for earth roads to:

$$RD = 5.8230 \frac{R^{0.2476}}{(\log t)^{2.002}\, C_1^{0.9335}\, C_2^{0.2848}} \qquad \text{(Eqn. 3-2)}$$

Simplifying;

$$RD = 5.8230 \frac{R^{0.2476}}{(\log 6")^{2.002}\, C_1^{0.9335}\, C_2^{0.2848}}$$

(Earth Roads Only)

$$RD = 9.6213 \frac{R^{0.2476}}{C_1^{0.9335}\, C_2^{0.2848}} \qquad \text{(Eqn. 3-3)}$$

where: C_1 = CBR of compacted subgrade

C_2 = CBR of uncompacted subgrade

Typically, C_1 will be the value of a soil that has been compacted to 90% of AASHTO T-99, while that for C_2 will be for 85% of AASHTO T-99.

[17]ARE Inc, Op. Cit

3.2 Differences in Design Procedure

As was discussed in Chapter 2, there are two levels of design presented in this guide; the Basic and the Advanced. The main differences in the two designs are due to the following:

- o Reliability
- o Seasonal effects
- o Traffic Estimation

Reliability: For the Basic design procedures, it is assumed that all roads are designed for the 50% reliability level. Therefore, the reliability factor (F_R) is 1.0. The Advanced design incorporates the use of reliability levels at 50%, 70% and 90%. Appendix C discusses in detail the development of these reliability factors.

Seasonal Effects: Only one season is assumed in the Basic design guide. The Advanced guide in Chapter 4 allows a maximum of 4 seasons for aggregate-surfaced road designs, and 2 for earth roads.

Traffic Estimation: For the Basic guide, only an estimation of the timber sale volume will be necessary. Typically, a conversion factor of 5,000 BF to 1 standard log truck is used. In addition, a 25% non-log truck factor is also used to account for non-truck traffic such as recreational and administrative traffic.

In addition, the computer program has defaults present to assist the designer. The defaults used are summarized below:

- o Allowable rut depth = 2 inches
- o Reliability factor = 1.0
- o Timber Conversion factor is 5,000 BF to 1 standard log truck
- o % non-truck traffic = 25%
- o Number of seasons = 1
- o Minimum aggregate thickness = 4 inches

However, the designer may over-ride these defaults at all times if more information is available.

The intent of the defaults provided is to simplify some of the data requirements. In particular, the road designer may often have no traffic estimates aside from timber sale volumes. One use of this Basic guide is to obtain estimates for budgeting purposes rather than for actual design purposes.

3.3 Aggregate-Surfaced Road Design

Assume the following variables:

- o Timber volume = 10 MMBF
- o Non-log truck factor = 25%
- o 1 yarder with 2 tandem axle loads of 80 kips, steering axle of 20 kips and tire pressure of 100 psi
- o Allowable rut depth = 2"
- o 1 season: Aggregate CBR = 50
  Subgrade CBR = 10
- o Trial thickness = 4 inches
- o Reliability factor = 1.0 (This is constant for all Basic designs)
- o Assume Aggregate loss is 1" per 10 MMBF
- o Assume 2 lane road

Step 1. Traffic

a. First convert timber volume to standard log trucks. The conversion factor is normally 5,000 BF to 1 standard log truck at tire pressure of 80 psi. However, 25% of the traffic is non-truck traffic.

$$\text{Loaded trucks} = \frac{10 \text{ MMBF } (1+25\%)}{5{,}000 \text{ BF}} = 2{,}500$$

b. Next, convert the number of log trucks to 18 kip ESALs. The equivalency factor for a standard log truck (10^k steering axle, two 35^k tandem axles, tire pressures of 80 psi) is:

$$
\begin{aligned}
EF_{truck} &= 0.45 + 2(1.36) = 3.17 \quad \text{(see Figure 15)}\\
\therefore R_{trucks} &= (\text{\# of trucks})\ (EF_{truck})\\
&= 2{,}500\ (3.17)\\
&= 7{,}925 \text{ ESALs}
\end{aligned}
$$

c. Convert the yarder to 18^k ESALs. The equivalency factor for 80-kip tandems is 10.91 and 20-kip single is 2.83 at 100 psi (Figure 16).

$$EF_{yarder} = (2 \text{ tandem axles})\ (10.91) + (1 \text{ single axle})\ (2.83)$$

$$EF_{yarder} = 24.65$$

Since there is only one pass of the yarder (this is a two-lane road):

$$R_{yarder} = (1 \text{ pass})\ (24.65)$$
$$= 25 \text{ ESALs (Round up)}$$

d. Total repetitions or passes of 18^k ESALs is then:

$$R_{18} = R_{truck} + R_{yarder}$$
$$= 7{,}925 + 25$$
$$R_{18} = 7{,}950 \text{ ESALs}$$

Step 2. Calculate R_{allow}

a. Since there is only one season, we can solve Equation 3-2 for aggregate thickness (t) directly, using the total number of repetitions for R. However, the ratio of C_1 to C_2 is 5, which does not meet the criterion discussed in Chapter 2. Therefore, aggregate CBR should be lowered to 40 to meet the 4:1 ratio.

$$RD_{allow} = 5.8230 \frac{R^{0.2476}}{(\log t)^{2.002}\ C_1^{\ 0.9335}\ C_2^{\ 0.2848}} \qquad \text{(Eqn. 3-2)}$$

Substituting;

$$2" = 5.8230 \frac{(7{,}950)\ 0.2476}{(\log t)^{2.002}\ (40)^{0.9335}\ (10)^{0.2848}}$$

$$2" = \frac{0.8924}{(\log t)^{2.002}}$$

Rearranging the terms;

$$(\log t)^{2.002} = 0.4462$$

Solving;

$$t = 4.66 \text{ inches}$$

Use t = 4.7 inches (round to nearest tenth of an inch)

In addition, 1 inch of aggregate is lost for every 10 MMBF of timber. Therefore, use <u>t = 4.7" + 1" = 5.7"</u>.

Finally, a chart solution is available in Figure 22. The traffic is the dependent variable and the aggregate thickness the independent variable. The 6 curves shown are for 6 different subgrade CBRs, at 5, 7, 9, 12, 16 and 20. It is also assumed that the aggregate CBR is 4 times the subgrade CBR ($C_1 = 4C_2$). The allowable rut depth is 2 inches. It can be observed that the abscissa does not extend beyond 50,000 18^k ESALs. This is because the algorithm was developed using data with a low number of passes of the test vehicle. Therefore, it would be extending the capabilities of the algorithm to apply it to traffic greater than 50,000 ESALs. It is recommended that the designer refer to the geotechnical section of their forest for further assistance if traffic exceeds 50,000 ESALs.

3.4 Earth Road Design

Assume the following variables.

- o Timber volume = 10 MMBF
- o 1 yarder with 2 tandem axle loads of 80 kips, steering axle of 20 kips and tire pressures of 100 psi
- o Non-truck factor = 25%
- o Allowable rut depth = 2"
- o 1 season: CBR of compacted subgrade = 15

  Subgrade CBR = 9

  The subgrade is an intermediate soil (Figure 6), so the multiplier of 1.7 is used.
- o Compacted thickness = 6 inches (this is a constant for earth roads)
- o Two-lane road

Step 1. Calculate 18^k ESALs

a. First, convert the timber volume and the yarder to 18^k ESALs as before (see Section 3.3, Step 1).

$$R_{18} = R_{truck} + R_{yarder} = 7{,}950 \text{ ESALs}$$

Step 2. Calculate Rut Depth

Using Equation 3-3:

$$RD = 9.6213 \frac{R^{0.2476}}{C_1^{0.9335}\, C_2^{0.2848}}$$

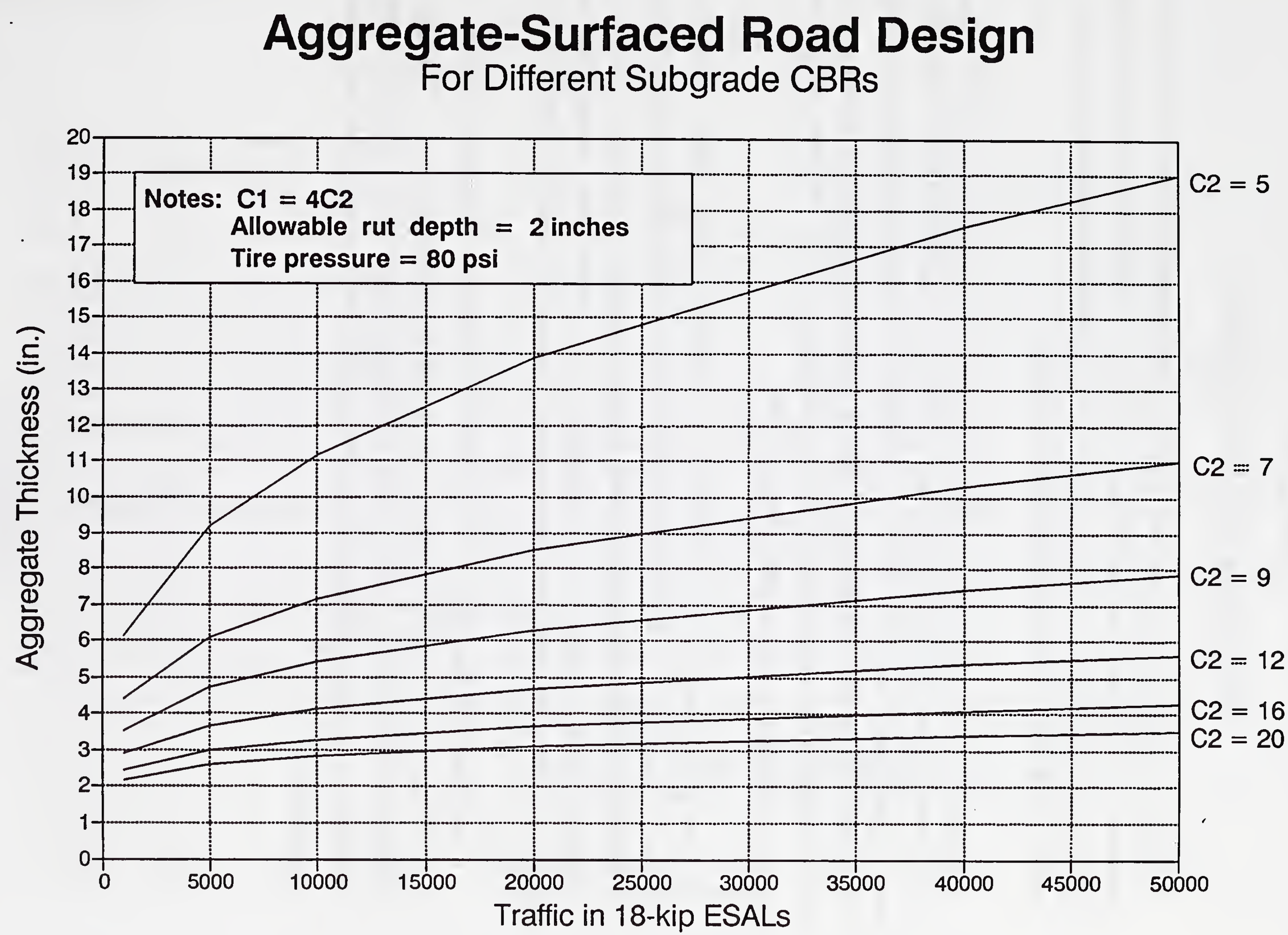

Figure 22. Aggregate-surfaced road design for different subgrade CBRs.

$$= 9.6213 \frac{(7{,}950)^{02476}}{(15)^{0.9335}\,(9)^{0.2848}}$$

RD = 3.8 inches (round up to nearest tenth)

Since a rut depth of 3.8 inches was calculated, the road designer may conclude that this is unacceptable. If a maximum rut depth of say, 3 inches is to be the failure criterion, then the engineer must reduce the traffic levels to obtain a smaller rut depth. An iterative process will be required. One alternative is to consider an aggregate-surfaced road design.

Alternatively, the designer may wish to limit the rut to three inches and estimate the amount of maintenance (number of bladings) which may be anticipated to support the traffic. Figure 20 can be used as a guideline to make the estimate. If the total rut is 4 inches and blading is to occur when the rut reaches 3 inches, then maintenance will occur at 75% of the anticipated rut. Based on the chart, this is expected when approximately 33% of the traffic has occurred. Therefore, about 3 bladings would be estimated to carry the total estimated traffic.

Figure 23 is a chart solution for earth roads. Similarly to Figure 22, traffic in 18^k ESALs is the abscissa. However, the rut depth is the ordinate. The designer will remember that for an earth road, the thickness (t) is kept constant at 6 inches. The four curves were developed for a uncompacted subgrade CBR of 3, 4, 5 and 6. The uncompacted state is assumed to be approximately equivalent to 85% of AASHTO T99, while the compacted layer is assumed to be at 90% of AASHTO T-99.

From Chapter 50 (see Figure 6), it was noted that CBR values increased by a factor of 1.7 for every 5% increase in compaction above 85% of T-99 for intermediate soils. Therefore, in the development of Figure 22, $C_1 = 1.7\ C_2$. Again, the design algorithm was not developed for subgrade CBRs below 3. If such conditions exist, then the designer should consider other approaches, such as geotextiles.

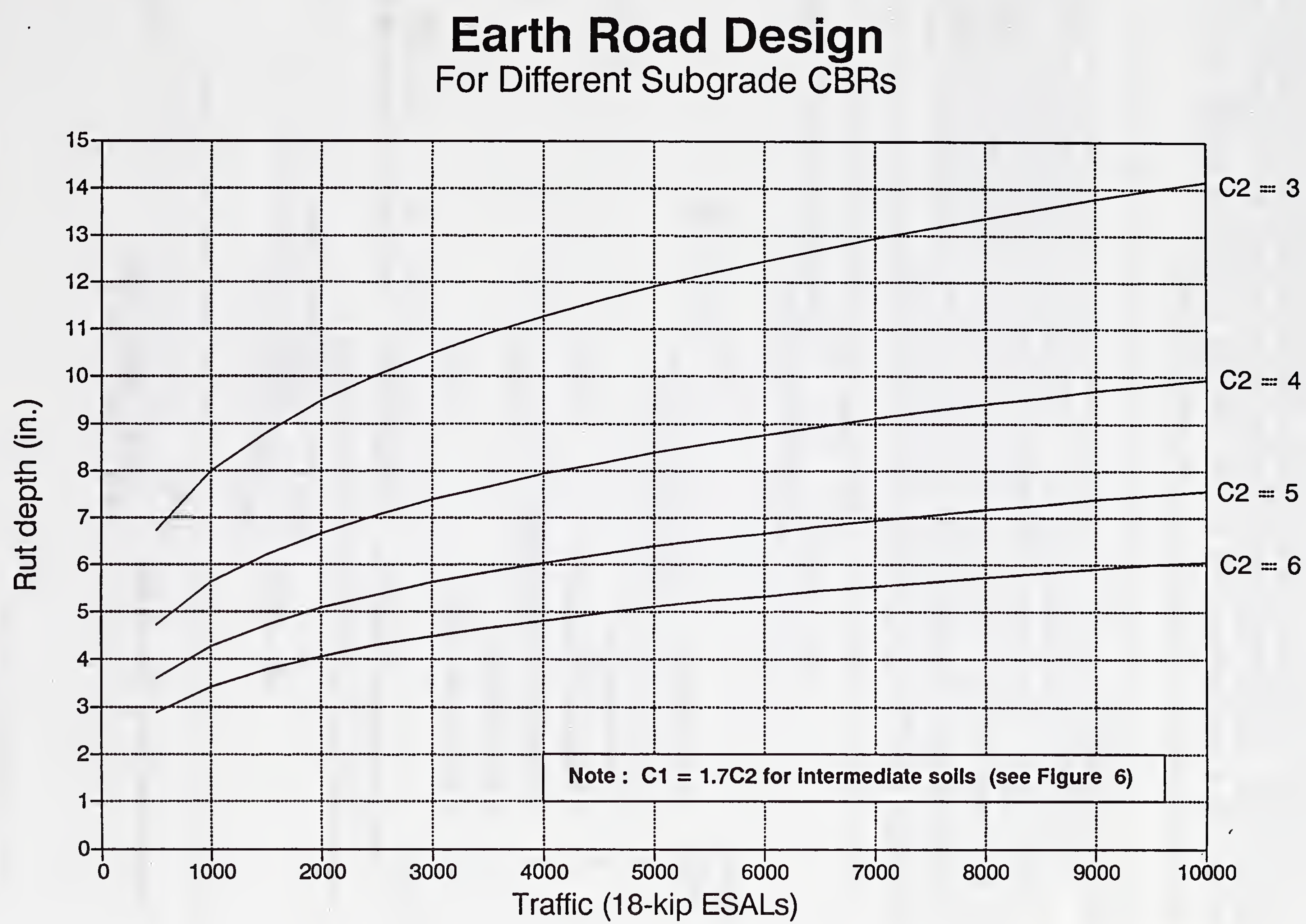

Figure 23. Earth road design for different subgrade CBRs.

4.0 ADVANCED DESIGN GUIDE

This chapter describes the design algorithm used in the proposed USFS Surfacing Thickness Program (STP). Some background on the selection of this procedure is provided as well as example problems for a gravel-surfaced road, an earth road, and a resurfacing example. Much of this information in Section 4.1 has already been presented in Chapter 3.

4.1 Design Algorithm

The algorithm selected for use in the STP was developed by the U.S. Army Corps of Engineers in 1978.[18] Existing rutting data at the Waterways Experiment Station for gravel-surfaced, earth and flexible pavements were utilized to develop deterioration and reliability models. A model was developed for aggregate-surfaced roads and this was selected for use by the Forest Service, as discussed in Chapters 1 and 3. The equation is reproduced below:

$$RD = 0.1741 \frac{P_k^{0.4704}\ t_p^{0.5695}\ R^{0.2476}}{(\log t)^{2.002}\ C_1^{0.9335}\ C_2^{0.2848}} \qquad \text{(Eqn. 3-1)}$$

where:

- RD = Rut depth, in.
- P_k = Equivalent single-wheel load (ESWL), kips
- t_p = Tire Pressure, psi
- t = Thickness of top layer, in.
- R = Repetitions of load or passes
- C_1 = CBR of top layer
- C_2 = CBR of bottom layer

Since the standard vehicle is an 18-kip ESAL (ESWL = 8.64 kips from Appendix B) with tire pressures of 80 psi, Equation 3-1 may be further simplified to:

$$RD = 0.1741 \frac{(8.64^{k})^{0.4704}\ (80\ \text{psi})^{0.5695}\ R^{0.2476}}{(\log t)^{2.002}\ C_1^{0.9335}\ C_2^{0.2848}}$$

(Aggregate Roads Only)
$$RD = 5.8230 \frac{R^{0.2476}}{(\log t)^{2.002}\ C_1^{0.9335}\ C_2^{0.2848}} \qquad \text{(Eqn. 3-2)}$$

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[18]Barber, V.C., Op. Cit.

The rut depth is expressed as a function of load, tire pressure, number of passes or repetitions of axle loads, surface thickness and layer material strengths. Rut depth was selected as the failure criterion, and this is consistent with most other design procedures for aggregate-surfaced and earth roads.[19] Different combinations and aggregate layer thicknesses, soil strengths and number of passes may be used to calculate rut depths.

The same equation (3-1) is used for the design of earth-surfaced roads with one modification. Although an unsurfaced model was also developed by the Corps, it made the assumption that the top layer was actually <u>weaker</u> than the bottom layer. The rationale was that the upper portion may be adversely affected by moisture and organic materials in a military situation. However, for Forest Service conditions, it is expected that compaction from construction traffic and trucks would offset these effects. Therefore, that model was <u>not</u> selected. The modification to Equation 3-2 involves the assumption that the thickness (t) of an earth road is assumed to be 6 inches. This is estimated to be the depth of compaction that would occur during construction. Therefore, the design algorithm may be further simplified for earth roads to:

$$RD = 5.8230 \frac{R^{0.2476}}{(\log t)^{2.002} C_1^{0.9335} C_2^{0.2848}} \qquad \text{(Eqn. 3-2)}$$

Simplifying;

$$RD = 5.8230 \frac{R^{0.2476}}{(\log 6")^{2.002} C_1^{0.9335} C_2^{0.2848}}$$

(Earth Roads Only)

$$RD = 9.6213 \frac{R^{0.2476}}{C_1^{0.9335} C_2^{0.2848}} \qquad \text{(Eqn. 3-3)}$$

where: C_1 = CBR of compacted subgrade
C_2 = CBR of uncompacted subgrade

Typically, C_1 will be the value for a soil that has been compacted to 90% AASHTO T-99, while that for C_2 will be for 85% AASHTO T-99.

[19]ARE Inc, Op. Cit

4.2 Seasonal Effects

In the Surfacing Thickness Program (STP), a maximum of 2 seasons for earth roads and 4 for aggregate-surfaced roads are possible. Miner's Hypothesis is used to sum up the damage ratios for each season. The following variables must be known.

- o Number of seasons. (i)
- o Estimated traffic for each season. ($R_{est,i}$)
- o Material CBRs for each season. (C_{1i}, C_{2i})
- o Trial thickness. (t)
- o Maximum allowable rut depth, (RD_{allow})

Aggregate-Surface Road Design Procedure. The steps in this procedure are:

1. For the first season, calculate R_{allow}, given that RD_{allow}, t, C_1, and C_2 are known using Eqn. 3-2.
2. Calculate the damage ratio of estimated traffic ($R_{est,1}$) to allowable traffic ($R_{allow,1}$) for the first season. If this ratio is less than or equal to 1,

$$\text{Damage Ratio} = \frac{R_{est,i}}{R_{allow,1}} \leq 1 \qquad \text{(Eqn. 4-1)}$$

   This indicates that the road as designed is adequate for the first season. If the damage ratio is greater than 1, then the following variables may be modified and the process iterated until the ratio is less than 1.

   - o Aggregate CBR (C_1)
   - o Estimated traffic ($R_{est,1}$)
   - o Thickness (t)
   - o Allowable rut depth (RD_{allow})

   However, the designer will typically only change the thickness before reiterating.

3. Repeat steps 1 and 2 for as many seasons as required. The allowable rut depth (RD_{allow}) and trial thickness (t) <u>must</u> be constant for all seasons.

4. Sum up the damage ratios.

$$\Sigma \frac{R_{est,i}}{R_{allow,i}} \leq 1 \qquad \text{(Eqn. 4-2)}$$

If the sum is less than or equal to 1, then the design is acceptable. If not, modifications to the variables listed in Step 2 are required and the whole process repeated. Equations 4-1 and 4-2 must be less than or equal to 1 for the design to be acceptable.

Earth Road Design Procedure: This procedure is slightly simpler than that for aggregate-surfaced roads. Eqn. 3-3 is used, and the steps are:

1. Calculate $R_{allow,1}$ for the season in which the lowest strength is anticipated given an allowable rut depth (RD_{allow}) using Eqn. 3-3.

2. Calculate the damage ratio as before. If the ratio is less than 1, the design is acceptable. If greater than 1, the traffic level (R) must be reduced or the allowable rut depth (RD_{allow}) increased. The CBRs of the subgrade (C_2) and compacted layer (C_1) may not be modified as this is the strength of in-situ material.

3. Repeat steps 1 and 2 for the next season. The allowable rut depth (RD_{allow}) must be constant for all seasons.

4. Sum up the damage ratios and check to see that it is less than or equal to 1 for an acceptable design. If the damage ratios are greater than 1, then the traffic level must be reduced or the engineer should consider an aggregate-surfaced road. Alternatively, a maintenance strategy is possible.

4.3 Resurfacing Design

The resurfacing design procedure is not included in the computer program and is applicable only to aggregate-surfaced roads. During the development of this project, the Advisory Board and the Consultant agreed upon a procedure that employs the program strictly as a tool to calculate thicknesses only. Figure 24 is a flowchart that illustrates the different steps in a resurfacing design. Basically, the approach assumes that there is an existing aggregate-surfaced road for which thickness and strength is estimated. This existing road may consist of a degraded or contaminated aggregate surface, such that the CBR is lower than its original design and the roadway may no longer be able

FILE: CBR-NEW

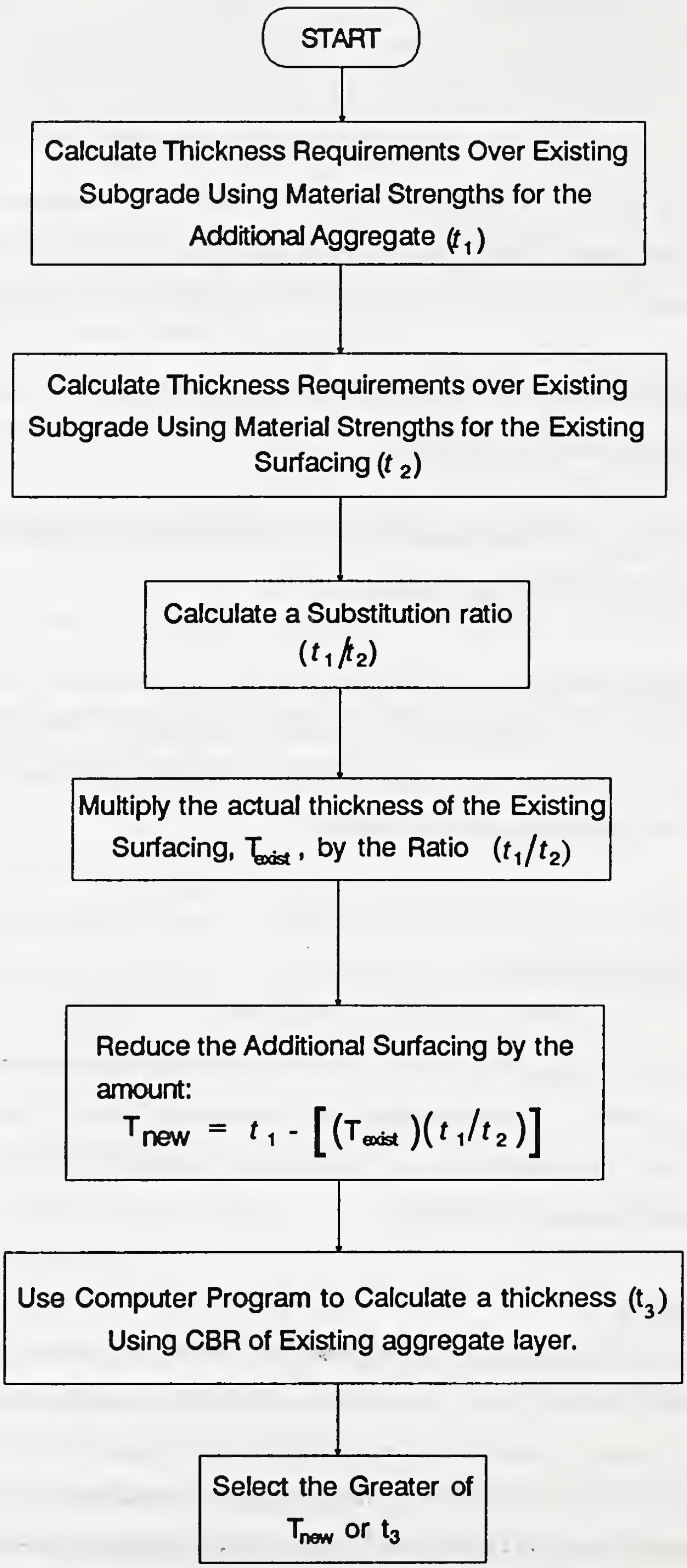


Figure 24. Flowchart For Resurfacing Design

to fulfill its intended function. Therefore, a new surfacing is required to bring the roadway back up to standard.

This procedure outlined below obtains an equivalency between the old and new material so as to convert the existing or old material to an equivalent thickness of new material. The steps required in this procedure are outlined below:

1. From Eqn. 3-2, a new thickness (t_1) using new material is calculated over the existing subgrade. The variables below are needed:
   - o allowable rut depth (RD_{allow})
   - o new material CBR (C_{new})
   - o Number of ESALs (R)
2. Next, calculate a similar thickness (t_2) except that the CBR of the aggregate layer (C_{old}) will be that of the existing or old aggregate. Chapter 2 contains guidelines on selection of the material strength.
3. A substitution ratio (t_1/t_2) is calculated next. If this ratio were 1/2, this would be interpreted to mean that 1 inch of the new material is equivalent to 2 inches of the old material.
4. Next, the existing thickness (t_{exist}) is converted to an equivalent thickness of new material using the substitution ratio.

$$t_{equiv} = (t_{exist})\ (t_1/t_2) \qquad \text{(Eqn. 4-3)}$$

5. The new surfacing thickness is then the difference between

$$t_{new} = t_1 - t_{equiv} \qquad \text{(Eqn. 4-4)}$$

6. Finally, a check is made to ensure that the new thickness calculated is adequate to protect the old surface material. This is done by calculating a thickness (t_3) that uses the CBR of the existing aggregate layer (c_{old}). The greater of t_3 or t_{new} or the minimum thickness is selected as the required resurfacing thickness.

4.4 Material Substitution

One facet of the aggregate-surface road design process is the use of or substitution with different materials, or a mixture of materials. Typically, a forest may want to reduce costs by using a less expensive or lower quality aggregate in some combination with higher quality aggregate. Figure 25 is a flowchart that outlines this procedure, which is very similar to that of the resurfacing design process.

FILE: SUB-FLOW

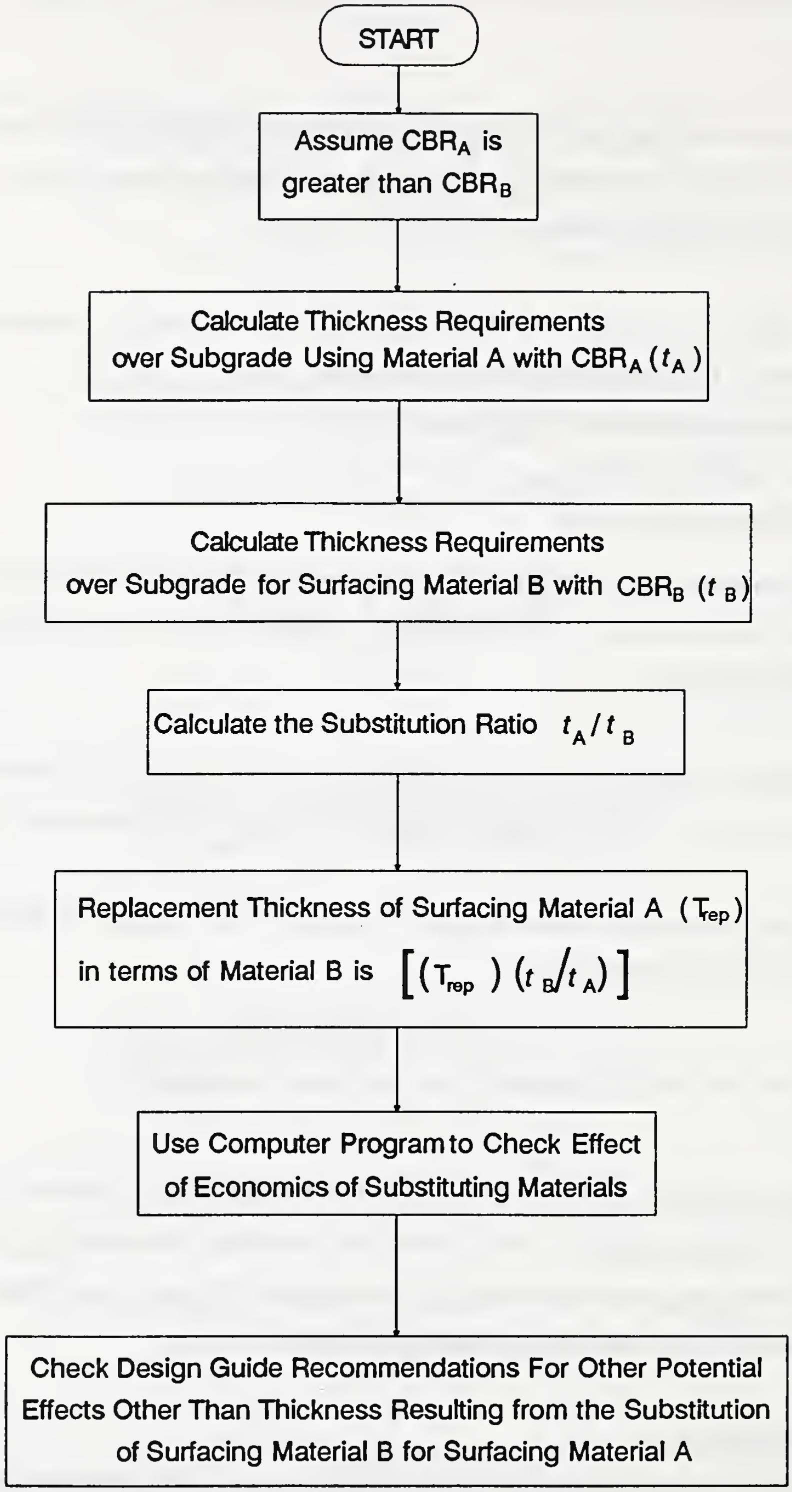


Figure 25. Flowchart For Substitution of Different Quality Sources of Surfacing

1. First, assume the CBR of aggregate A is higher than that for Aggregate B, i.e. $CBR_A > CBR_B$.

2. Then calculate the thickness (t_A) required if only Aggregate A is used.

3. Next, calculate the thickness (t_B) required if only Aggregate B is used.

4. A substitution ratio (t_B/t_A) is then obtained. This ratio is read as t_B inches of material B to be equivalent to t_A inches of material A.

5. Next, a portion of t_A is to be replaced with material B. This replacement thickness is t_{rep}. Therefore, the amount of material B (t_{sub}) required to substitute for t_{rep} will be:

$$t_{sub} = (t_{rep})\ (t_B/t_A) \qquad \text{(Eqn. 4-5)}$$

6. The surfacing thickness program is then used to perform the economic analysis on the costs and benefits of using a lower quality aggregate as a substitute.

4.5 Example of Earth Road Design

Assume the following variables are known:

- o 1 season
- o Timber volume = 8 MMBF
- o Non-log truck factor = 25%
- o t = 6 inches (This is a constant for earth roads.)
- o Madill 044 Yarder (2 tandem axle loads = $80^{k\ each}$, steering axle = 10^k, t_p = 100 psi)
- o Subgrade CBR = 10
- o Compacted CBR = 20 (assuming 90% compaction level and based on cohesive soils, Fig. 6)
- o Reliability Factor = 1.0 (This is a constant for earth roads)
- o 1 lane earth road

Step 1. Traffic Calculations

a. First, timber volume has to be converted to number of log trucks. Typically, a conversion factor of 5 MBF = 1 standard log truck is used although other conversions may be available from different regions or forests. There is a non-log truck factor of 25%. For a standard log truck with two 35 kip tandem axles, and a 10-kip steering axle the equivalency factor at 80 psi is 2(1.36) + 1 (0.45) = 3.17 (see Figure 15).

$$\text{No. of trucks} = \frac{8 \text{ MMBF}}{5 \text{ MBF}} (1+25\%) = 2{,}000 \text{ standard log trucks}$$

$$\therefore R_{trucks} = (2{,}000)(3.17) = 6{,}340 \text{ ESALs}$$

b. Since this is a one lane road, the number of empty log trucks must also be included. Typically, an empty log truck will have a total weight of 26 kips, within one 10 kip single-axle, single wheel, and one 16 kip tandem-axle, dual wheel. (The second tandem is usually "piggy-backed".) Therefore, the equivalency factor for an empty log truck at 80 psi is:

$$1(0.45) + 1(0.31) = 0.76 \text{ (Figure 15)}$$

$$\therefore R_{trucks} = (2{,}000)(0.76) = 1{,}520 \text{ ESALs}$$

c. The yarder has to be converted to 18^k ESALs as well, using an equivalency factors from Figure 16; the equivalency factor for a Madill 044 is 2(10.91) + 1(0.76) = 22.58 (Figure 16). (Appendix B discusses the calculation of equivalency factors in more detail.) Since this is a one lane road, the yarder makes 2 passes:

$$R_{yarder} = (\#\text{ passes})(\text{Equivalency factor})$$
$$= (2 \text{ passes})(22.58)$$
$$R_{yarder} = 46 \text{ ESALs (Round-up)}$$

d. Total number of Repetitions of ESALs is then:

$$R_{total} = R_{truck} + R_{yarder} + R_{empty}$$
$$= 6{,}340 + 46 + 1{,}520$$
$$R_{total} = 7{,}906 \text{ ESALs}$$

Step 2. Rut Depth

$$RD = 9.6213 \left(\frac{R^{0.2476}}{C_1^{0.9335} C_2^{0.2848}}\right) \quad \text{(Eqn 3-3)}$$

$$= 9.6213 \left(\frac{(7{,}906 \text{ ESALs})^{0.2476}}{20^{0.9335}\, 10^{0.2848}}\right)$$

$$RD = 2.9 \text{ Inches (Round up to nearest tenth of an inch)}$$

Since a rut depth of 2.9 Inches was calculated, the road designer may conclude that this is acceptable. However, if a maximum rut depth of, say, 3 Inches is to be the failure criterion, and the

calculated rut depth is 4 inches, then the engineer must reduce the traffic levels to obtain a smaller rut depth. A process of iteration will be necessary.

Alternatively, the designer may wish to limit the rut to three inches and estimate the amount of maintenance (number of bladings) which may be anticipated to support the traffic. Figure 20 can be used as a guideline to make the estimate. If the total rut is 4 inches and blading is to occur when the rut reaches 3.0 inches, then maintenance will occur at 75% of the anticipated rut. Based on the chart, this is expected when approximately 33% of the traffic has occurred. Therefore, about 3 bladings would be estimated to carry a total traffic of 8 MMBF. For this example, each blading would be expected to occur after approximately 2.6 MMBF.

4.6 Example of Aggregate-Surfaced Road Design

The following conditions are assumed:

a. Traffic

- o 4,500 off highway log trucks, with 2 tandem axle loads of 40 kips, a steering axle of 10 kips and tire pressures of 100 psi. 96 percent of trucks will operate during the dry season, the remainder in the wet season.
- o Skagit T-100-HD with yarder. 2 tandem axle loads of 120 kips each, a steering axle of 20^k and tire pressures of 100 psi.

b. Seasonal Effects

- o 2 seasons are present: wet and dry.

c. Material Characteristics

The aggregate is a granular material classified as GW. Roller compaction is specified for the construction. The subgrade material is based on laboratory data, and is determined to be a SM_u material, with a CBR of 15 in the dry season and 10 during the wet season.

d. Other Inputs

- o Allowable rut depth = 2"
- o Initial trial thickness = 4"
- o Assume one lane road, Traffic Service Level C

Step 1. Traffic

a. First convert the log trucks to standard 18-kip ESALs. From Figure 16, the equivalency factor for a loaded truck is 2(2.92) + 1(0.76) = 6.60.

$$\therefore R_{trucks,\ loaded} = (\#\ trips)\ (Equivalency\ factor)$$
$$= (4{,}500)\ (6.60)$$
$$R_{truck,\ loaded} = 29{,}700\ ESALs$$

b. Since this is a one lane road, the effect of empty log trucks must also be calculated. Assume an empty log truck to have 1 tandem axle of 16 kips (the other tandem is "piggy-backed") and a steering axle of 10 kips, at tire pressures of 100 psi. From Figure 16, the equivalency factor obtained is:

$$1(0.51) + 1(0.76) = 1.27$$
$$R_{trucks,\ empty} = (\#\ trucks)\ (Equivalency\ factor)$$
$$= (4{,}500)\ (1.27)$$
$$R_{truck,\ empty} = 5{,}715\ ESALs$$

c. Convert yarder to ESALs. From Figure 16, the equivalency factors for two 120 kip tandem axles and a steering axle of 20 kips at 100 psi is 2(23.57) + 1(2.83) = 49.97. Since this is a one lane road, the yarder makes two passes.

$$\therefore R_{yarder} = (\#\ trips)\ (Equivalency\ factor)$$
$$= (2)\ (49.97)$$
$$R_{yarder} = 100\ ESALs$$

Step 2. Reliability Factors

Since this is a Traffic Service Level C road, the reliability factor is 1.44 (Figure 21). Therefore, the 18^k ESALs calculated in Step 1 must be increased by this factor.

Step 3. Calculate R_{allow} for Dry Season

a. 96% of traffic will operate during the dry season. Also assume that the yarder travels over the road only when it is dry.

$$\therefore R_{dry} = [(96\%)\ (R_{trucks}) + R_{yarder}]\ F_R$$
$$= [0.96\ (29{,}700 + 5{,}715) + 100]\ (1.44)$$
$$R_{dry} = 49{,}102\ ESALs$$

b. For a roller-compacted material, the Forest Service has specifications that indicate the aggregate should be compacted to 90-95% of AASHTO T-99 (see Section 2.2). For this example, use 95% AASHTO T-99. Since the material is classified as GW, the CBR may be obtained in various ways:

i) From Figure 6, the USFS provides a general range of 17 to 33 @ 85% compaction, with a multiplier of 1.3 for each 5% increase in T-99 compaction above 85%. For this example, select a CBR of 25 @ 85%. Therefore, at 95% compaction,

$$C_1 = (25)\ (1.3)\ (1.3) = 42$$

ii) Alternatively, if this example was located in the Willamette N.F., Figure 5, which provides site-specific historical laboratory data, may also be used. For a GW material at 95% compaction, there is a CBR range of 9 to 56, with an average of 25. As the user can see, this value is half that of option (i). This highlights the weakness of using "general" tables and the need for site-specific CBRs. For this example, select a CBR of 42. In the wet season, assume the strength decreases, to 30. Therefore, in summary, we have,

Dry season: $C_1 = 42$ $\quad C_2 = 15$
Wet season: $C_1 = 30$ $\quad C_2 = 10$

The ratio of C_1 to C_2 in the dry season is 42/15 = 2.8
The ratio of C_1 to C_2 in the wet season is 30/10 = 3.0

Since both ratios are less than 4.0, this is acceptable. If the ratio had exceeded 4.0, then the aggregate CBR should be lowered until it meets this criterion.

c. Solve Eqn. 3-2 for R_{allow}.

$$RD = 5.8230 \frac{R^{0.2476}}{(\log t)^{2.002}\ C_1^{\ 0.9335}\ C_2^{\ 0.2848}} \qquad \text{(Eqn 3-2)}$$

Substituting;

$$2'' = 5.8230 \frac{R^{0.2476}}{(\log 4'')^{2.002}\ (42)^{0.9335}\ (15)^{0.2848}}$$

$$2'' = 0.2270\ R^{0.2476}$$

Re-arranging the terms;

$$R^{0.2476} = 8.8100$$

$$0.2476 \log R = \log 8.8100$$

$$\log R = \frac{\log 8.8100}{0.2476}$$

$$= 3.8165$$

$$\therefore R_{allow,\ dry} = 6{,}555 \text{ ESALs}$$

Step 4. Calculate Damage Ratio for Dry Season

$$\therefore R_{allow,\ dry} = 6{,}555 \text{ ESALs (from Step 3c)}$$

$$R_{dry} = 49{,}102 \text{ ESALs (from Step 3a)}$$

$$\therefore \frac{R_{dry}}{R_{allow,dry}} = \frac{49{,}102}{6{,}555} = 7.49 > 1.0$$

Since the damage ratio is greater than 1, this is unacceptable. Therefore, the aggregate thickness must be increased, and the process repeated.

Step 5. Repeat Steps 3 and 4

Increase thickness to t = 5". Then calculate R_{allow} (Step 3) as before:

$$R_{allow,\ dry} = 21{,}910 \text{ ESALs.}$$

Then recalculate damage ratios:

$$\therefore \frac{R_{dry}}{R_{allow,dry}} = \frac{49{,}102}{21{,}910} = 2.24 > 1.0$$

Since the damage ratio is greater than 1.0, this is not acceptable. Repeat steps 3 and 4 for t = 6 inches.

Step 6. Repeat Steps 3 and 4

Increase thickness to t = 6". Then calculate R_{allow} (Step 3) as before:

$$R_{allow,\ dry} = 52{,}178 \text{ ESALs.}$$

(Note: The STP program will perform this iteration @ 0.1 inch increments.).

Then recalculate damage ratios:

$$\therefore \frac{R_{dry}}{R_{allow,dry}} = \frac{49{,}102}{52{,}178} = 0.94 \qquad < 1.0$$

Since the damage ratio is less than 1.0, this is acceptable. Continue with the next step.

Step 7. Calculate R_{allow} for Wet Season

a. 4% of truck traffic will operate during the wet season.

$$\therefore R_{wet} = (4\%)\ (R_{truck})\ (F_R)$$

$$= (0.04)\ (29{,}700 + 5{,}715)\ (1.44)$$

$$R_{wet} = 2{,}040 \text{ ESALs}$$

b. Using the same assumption as before for rut depth but using the new thickness; i.e. RD_{allow}=2" and t=6" as well as the wet material characteristics, we obtain:

$$2" = 5.8230 \frac{R^{0.2476}}{(\log 6")^{2.002}\ (30)^{0.9335}\ (10)^{0.2848}}$$

Solving,

$$R_{allow,wet} = 9{,}205 \text{ ESALs}$$

Step 8. Calculate Damage Ratio for Wet Season

$$R_{allow,wet} = 9{,}205 \text{ ESALs (from Step 7b)}$$

$$R_{wet} = 2{,}040 \text{ ESALs (from Step 7a)}$$

$$\therefore \frac{R_{wet}}{R_{allow,wet}} = \frac{2{,}040}{9{,}205} = 0.22 < 1$$

Since the damage ratio is less than 1.0, the design is acceptable.

Step 9. Check Sum of Damage Ratios

$$\frac{R_{dry}}{R_{allow,dry}} + \frac{R_{wet}}{R_{allow,wet}} = 0.94 + 0.22 = 1.16 > 1.0$$

Since the sum of the damage ratios is greater than 1.0, the design is unacceptable. A new trial thickness must be assumed and steps 2 through 9 re-iterated.

Step 10. Recalculate $R_{allow,dry}$ and $R_{allow,wet}$

Assume t = 7". The following may be calculated as before.

$R_{allow,dry}$ = 101,695 ESALs (Step 3c)

$R_{allow,wet}$ = 17,940 ESALs (Step 7b)

$$\text{Dry damage ratio} = \frac{49{,}102}{101{,}695} = 0.48 < 1.0 \qquad \text{(Step 4)}$$

$$\text{Wet damage ratio} = \frac{2{,}040}{17{,}940} = 0.14 < 1.0 \qquad \text{(Step 8)}$$

Both damage ratios are less than 1.0, which is acceptable. The sum of both ratios is 0.48 + 0.14 = 0.62 < 1.0, which is also acceptable. Therefore the final design aggregate thickness is 7 inches. (This does not consider aggregate loss). Iteration at 0.1 inch increments would have resulted in a smaller thickness.

4.7 Example of Resurfacing Design

An existing pavement with the following properties (see Figure 26) requires resurfacing.

C_{Old}	=	20
C_2	=	10
t_{exist}	=	4 inches
R	=	30,000 ESALs
RD_{allow}	=	2 inches

The new aggregate is a fractured rock, with a plasticity index of 5. The road will be exposed to wet conditions for 4 months of the year, when it may be expected that it will approach saturation levels. However, the aggregate has excellent drainage qualities.

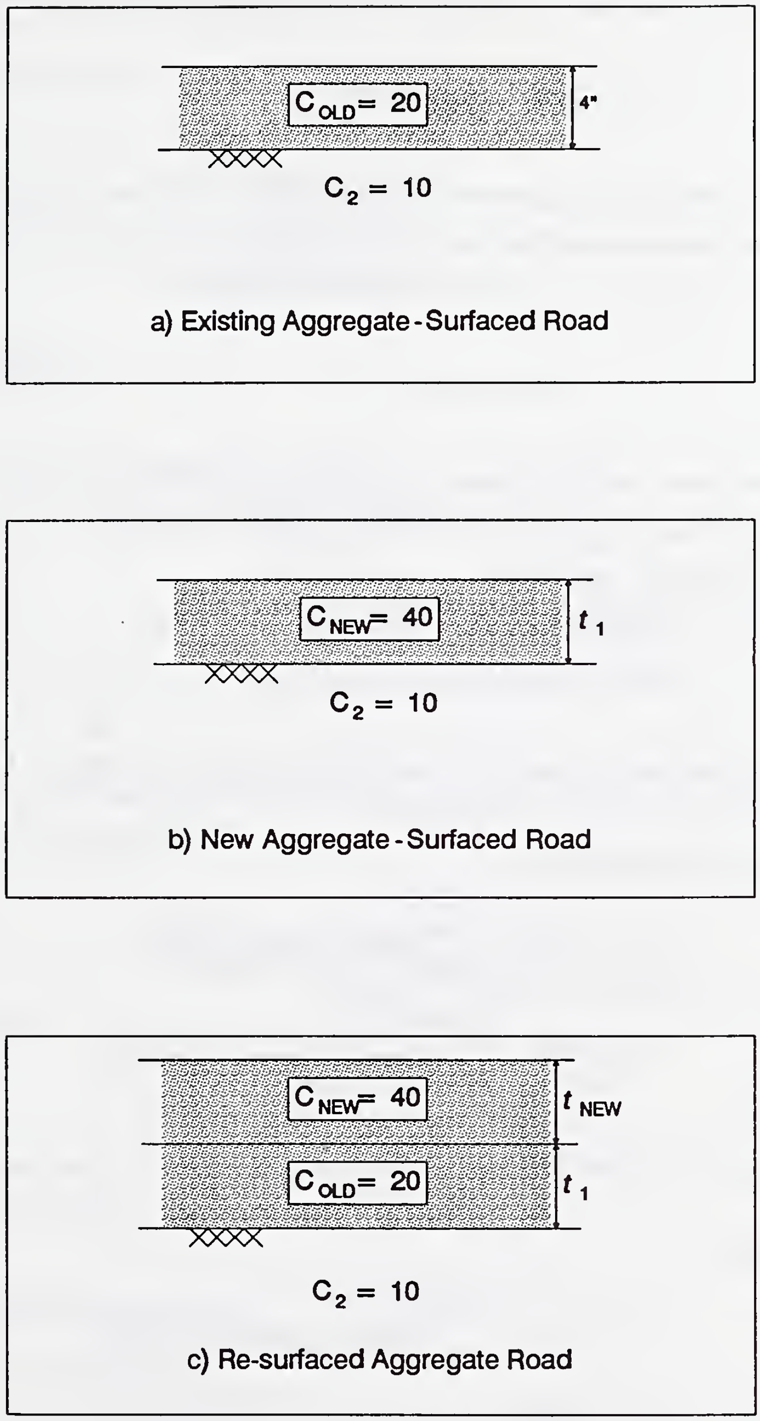


Figure 26. Resurfacing Design Example

Step 1. Calculate CBRs of new aggregate (C_{new})

Since this is a fractured rock, the layer coefficient (a-value) is 0.08 (see Figure 7). The PI is 5 and this is intended as a surfacing material, so we can add 0.01 to the layer coefficient.

$$\therefore a = 0.08 + 0.01 = 0.09$$

In addition, the road will be exposed to wet condition for 4 months of the year (33% of time), but it has excellent drainage qualities (drains to 50% saturation in 2 hours). Therefore, the moisture (m_i) factor is 1.20 (Figure 8). The layer coefficient is now:

$$a = (0.09)(1.20) = 0.108$$

To convert this value to CBR, Figure 9 is utilized. From this chart, for a = 0.108, the CBR is approximately 45 (i.e., $C_{new} = 45$). This assumes 100% of AASHTO T-180. Assume 95% of T-99 is achieved in the field. Therefore:

100% T-99 CBR = 45 x 0.975 = 44

95% T-99 CBR = 44 ÷ 1.3 = 34

Therefore, the user should select 34. Note that this does not violate the 4:1 criterion.

Step 2. Calculate t_1 Using Eqn. 3-2.

$$RD = 5.8230 \frac{(R)^{0.2476}}{(\log t)^{2.002}\, C_1^{0.9335}\, C_2^{0.2848}} \qquad \text{(Eqn 3-2)}$$

Substituting;

$$2" = 5.8230 \frac{(30{,}000)^{0.2476}}{(\log t_1)^{2.002}\, (34)^{0.9335}\, (10)^{0.2848}}$$

Solving for t_1;

$$\therefore t_1 = 7.07"$$

Step 3. Calculate t_2

$$2" = 5.8230 \frac{(30{,}000)^{0.2476}}{(\log t_2)^{2.002}\, (20)^{0.9335}\, (10)^{0.2848}}$$

$$\therefore t_2 = 12.25"$$

Step 4. Calculate t_1/t_2

$$t_1/t_2 = 7.07"/12.25" = 0.58$$

In short, 1 inch of old or existing material is approximately equivalent to 0.58 inches of new material.

Step 5. Convert Existing Thickness

$$t_{equiv} = (t_{exist})\,(t_1/t_2) \qquad \text{(Eqn. 4-3)}$$
$$= (4")\,(0.58)$$
$$t_{equiv} = 2.31 \text{ inches}$$

Step 6. Calculate t_{new}

$$t_{new} = t_1 - t_{equiv} \qquad \text{(Eqn. 4-4)}$$
$$= 7.07" - 2.31"$$
$$= 4.76"$$
$$t_{new} = 4.8 \text{ inches (Round up to nearest 0.1 inch)}$$

Step 7. Check t_3

As a check, t_3 is calculated using the existing aggregate CBR as C_2. Note that C_2 is now 20, therefore the 4:1 ratio still holds.

$$2" = 5.8230 \quad \frac{(30{,}000)^{0.2476}}{(\log t_3)^{2.002}\,(34)^{0.9335}\,(20)^{0.2848}}$$

Solving for t_3;

$$t_3 = 5.9" \text{ (Round up to nearest 0.1 inch)}$$

Since t_{new} is less than t_3 (4.8" < 5.9"), use t_3 as the design thickness. If $t_3 < t_{new}$, then the design thickness used should be t_{new}.

4.8 Example of Material Substitutions

a. Assume the following:

R = 30,000 ESALs

C_A = 40 (CBR of material A)

C_B = 30 (CBR of material B)

C_2 = 10

RD_{allow} = 2 inches

Note that the 4:1 ratio is still valid for both cases.

b. Calculate t_A using material A. From Eqn. 3-2, we can solve for t;

$$t_A = 6.13 \text{ inches}$$

c. Calculate t_B using material B. From Eqn. 3-2;

$$t_B = 7.95 \text{ inches}$$

d. Calculate substitution ratio;

$$t_B/t_A = 7.95/6.13 = 1.30$$

This is interpreted to mean 1.30 inches of material B is equivalent to 1 inch of material A.

e. Assume that 4" (t_{rep}) of material A is to be replaced with material B. Calculate the substitution thickness (t_{sub});

$$t_{sub} = (t_{rep})\ (t_B/t_A) \qquad \text{(Eqn. 3-8)}$$

$$= (4")\ (1.30)$$

$$t_{sub} = 5.2 \text{ inches}$$

Therefore, if 4" of material A (the stronger material) is to be replaced, it requires 5.2" of material B (the weaker material).

5.0 ECONOMIC ANALYSIS

The principles of engineering economy can be applied to pavement projects at two levels. The first level is concerned with the management decisions required to determine the feasibility and programming of a project; the second requires that the selected project be cost-effective, and that the cost-effectiveness be maximized. The second level might be considered suboptimization with respect to the first level, but it is more important to the designer. This is achieved by considering a variety of alternatives capable of satisfying the overall project requirements.

The major difference in economic evaluation between these two levels of pavement management concerns the amount of detail and information required. Otherwise, the basic principles involved are the same. This chapter considers the second level of economic analysis only. The information in this chapter is summarized from the 1986 AASHTO Guide for Design of Pavement Structures.

5.1 Life Cycle Costs

It is essential in economic evaluation that all costs occurring during the life of the facility be included. The term "life-cycle costs" was coined around 1970 for use with pavements. Life-cycle costs refer to all costs (and, in the complete sense, all benefits) which are involved in the provision of a pavement during its complete life cycle. These include, of course, construction costs, maintenance costs, rehabilitation costs, etc. An example of life-cycle costs used to compare the costs and value of two automobiles for purchase includes: (1) purchase price, (2) gasoline and operating costs, such as buying tires, (3) repairs (maintenance), and (4) trade-in value (salvage), etc. The same kind of comparison should be recognized for pavements.

Also required, of course, is a consideration of the useful life of the car. An inexpensive car may last 4 years while an expensive one, carefully selected, may last 15 years. Since all of these costs do not occur at the same time, it is useful to determine the amount of money which could be invested at a fixed time (usually the beginning) and that would earn enough money at a specific interest rate to permit payment of all costs when they occur. Thus, an interest rate or time value of money becomes important in the calculations.

"Life-cycle costs" then is a term coined to call special attention to the fact that a complete and current economic analysis is needed if alternatives are to be truly and correctly compared to each other.

The analysis period refers to the time for which the economic analysis is to be conducted. The analysis period can include provision for periodic surface renewal or rehabilitation strategies which will

extend the overall service life of a pavement structure before complete reconstruction is required.

5.2 Factors Involved in Pavements Costs and Benefits

The major initial and recurring costs that should be considered in the economic evaluation of alternative road design strategies include the following:

1. Agency costs
   a. Initial construction costs
   b. Maintenance costs, recurring throughout the design period, eg. blading
   c. Salvage or residual value at the end of the design period (which may be a "negative cost")
   d. Engineering and administration costs
   e. Traffic control costs if any are involved
2. User costs

However, user costs are generally difficult to quantify and in the case of the Forest Service where roads may be restricted to the public, they will not be included in this discussion. If interested, the designer may refer to AASHTO for a more detailed discussion.

Initial Construction Costs: Computing the initial cost of construction involves the calculation of material quantities to be provided in each pavement structure and multiplication by their unit prices. Material quantities are generally direct functions of their thicknesses in the structure. They are also functions of thicknesses of other layers and the width of pavement and shoulders. Engineering and administrative costs associated with the design should also be included. Each forest should have local cost estimating guides available to assist the designer.

Maintenance Cost: Maintenance is defined as "the preservation of the entire roadway, including surface, shoulders, roadside, structures, and such traffic-control devices as are necessary for its safe and efficient utilization." Pavement maintenance then involves the preservation of the pavement including shoulders and related drainage. The maintenance cost is the estimation of all costs which are essential to preserve the roadway at the desired level of service. This can include blading and reshaping of the pavement surface and shoulders. Again, the designer is referred to the local cost estimating guide for guidelines on maintenance costs.

Salvage or Residual Value: Salvage or residual value is used by some agencies in economic evaluation. It can be significant in the case of pavements because it involves the value of reusable materials at the end of the design period. With the depletion of resources, such materials can become

increasingly important in the future, especially when used in a new pavement by reworking or reprocessing.

The salvage value of a material depends on several factors, such as volume and position of the material, contamination, age or durability, anticipated use at the end of the design period, etc. Typically, it is represented as a percentage of the original cost. Salvage value can be difficult to calculate; the choice of values to be assigned will pose a problem for the engineer for example, what value to assign to an aggregate that is 5 years old. Each agency should have its own methods of determining this value. For example, the Willamette N.F. uses remaining life beyond the design period as salvage value.

5.3 Methods of Economic Evaluation

There are several methods of economic analyses that are applicable to the evaluation of alternative pavement design strategies.

1. Equivalent uniform annual cost method, often simply termed the "annual cost method."
2. Present worth method for:
   a. costs,
   b. benefits, or
   c. benefits minus costs, usually termed the "net present worth" or "net present value method."
3. Rate-of-return method
4. Benefit-cost ratio method
5. Cost-effectiveness method

Of these, only the first two have been selected for inclusion in the design guide. They are also the two most widely accepted methods of economic analysis used in engineering design.

Equivalent Uniform Annual Cost Method

The equivalent uniform annual cost (EUAC) method combines all initial capital costs and all recurring future expenses into equal annual payments over the analysis period. The primary advantage of this method is that alternatives with different service lives can be compared. Figure 27a illustrates the equivalent cash flows. The basic equation is:

$$EUAC = I * crf + MO - S * ssf \qquad \text{(Eqn. 5-1)}$$

where:

EUAC = Equivalent Uniform Annual Cost for an analysis period of n years.

I = Initial capital costs of construction.

crf = Capital recovery factor for interest rate i and n years

$$= \frac{i\,(1 + i)^n}{(1 + i)^n - 1}$$

ssf = sinking fund factor for interest rate i and n years

$$= \frac{i}{(1 + i)^n - 1}$$

MO = Avg. annual maintenance plus operation costs

S = Salvage value, if any, at the end of n years

Net Present Worth (NPW) Method

The net present worth (Figure 27b) is comparable to the EUAC method for comparable conditions; e.g., cost, discount rates and analysis periods. It considers costs and benefits together and involves the discounting of all future sums to the present, using a discount factor. There are two discount factors available, one for a uniform series and one for single future amounts. The present rate factor for single future amounts is:

$$\text{pwf} = \frac{1}{(1 + i)^n} \qquad \text{(Eqn. 5-2a)}$$

The present worth factor for a future uniform series is typically represented as pwf' and is calculated as shown below:

$$\text{pwf}' = \frac{(1 + i)^n - 1}{i\,(1 + i)^n} \qquad \text{(Eqn. 5-2b)}$$

where:

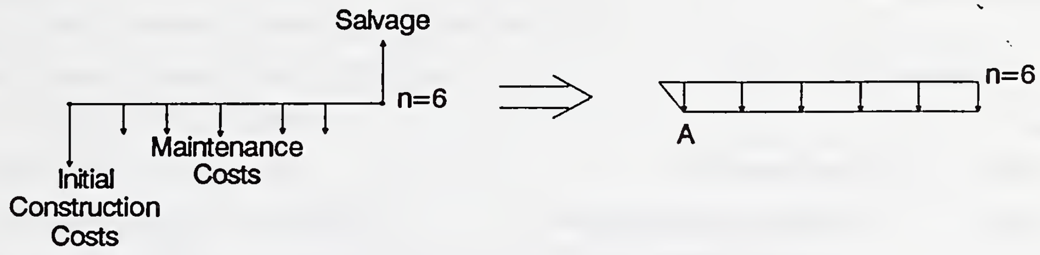
pwf = present worth factor for future amount

pwf' = present worth factor for future uniform series

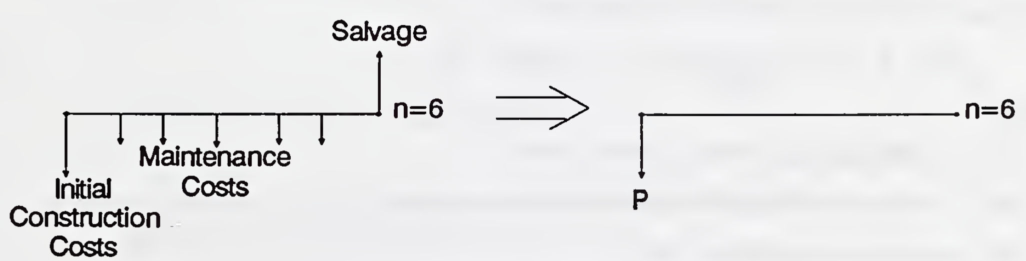
I = interest or discount rate

n = number of years to when the sum will be expended, or saved

The NPW is the difference between the present worth of benefits and the present worth of costs. Benefits must exceed costs if a project is to be justified on economic grounds. The benefits include direct, indirect and non-user benefits accruing from the project. In cases where the Forest Service



a) EUAC Method. All Costs Are Combined Into Equal Annual Amounts (A).



b) Net Present Worth Method. All Costs and Benefits Are Combined Into One Value (P) at a Single Instant of Time.

Figure 27. Illustrations of EUAC and NPW Methods

cannot specifically quantify these benefits, the analysis will use costs only. Most agencies do not have available data to relate user costs to pavement factors. In this case, the project with the least present worth of costs should be selected. Only Equation 5-5 is used in this case. The NPW equations can be represented as:

$$NPW = PW_B - PW_C \qquad \text{(Eqn. 5-3)}$$

where:

NPW = net present worth

PW_B = present worth of benefits

PW_C = present worth of costs

The present worth of benefits is expressed as:

$$PW_B = pwf' \cdot [DU + IU + NU] \qquad \text{(Eqn. 5-4)}$$

where:

DU = annual direct user benefit

IU = annual indirect user benefits

NU = annual nonuser benefits accruing from the project

The present worth of costs is expressed as:

$$PW_C = IC + (pwf')[MO + UC] - (pwf) \cdot [S] \qquad \text{(Eqn. 5-5)}$$

where:

IC = initial capital costs of construction

MO = annual maintenance plus operation costs

UC = annual user costs, if any

S = salvage value, if any, at end of design period

There are a number of advantages inherent in the net present value method that make it perhaps the most feasible for the highway field in comparison to the "traditional" annual cost and benefit-cost methods. These advantages include the following:

1. The benefits and costs of a project are related and expressed as a single value.
2. All monetary costs and benefits are expressed in present-day terms.
3. The answer is given as a total payoff for the project.

Disadvantages to the net present value method, include the following:

1. The results, in terms of a lump sum, may not be easily understandable to some people as a rate of return or annual cost. In fact, the summation of costs in this form can tend to act

as a deterrent to investment in some cases.

2. Alternatives with different service lives cannot be easily compared.

5.4 Examples

Given the following conditions, calculate the NPW and EUAC.

- o Initial cost of construction = \$80,000
- o Analysis period = 10 years
- o Blading cost = \$800/year
- o Spot rocking cost = \$1,000/year
- o Engineering and administration costs = 10% of initial construction
- o Salvage value at end of analysis period = none
- o Discount rate = 4%
- o No benefits can be quantified

Calculate EUAC: Using Eqn. 5-1,

$$EUAC = I * crf + MO - S * ssf$$

where:

$$crf = \frac{i(1+i)^n}{(1+i)^n - 1} = \frac{4\%(1+4\%)^{10}}{(1+4\%)^{10} - 1} = 0.1233$$

$$ssf = \frac{i}{(1+i)^n - 1} = \frac{4\%}{(1+4\%)^{10} - 1} = 0.0833$$

I = Construction + Engineering + Administrations Costs
= \$80,000 + 10% (\$80,000) = \$88,000

MO = Blading Cost + Spot Rocking Cost = \$1,800/year

S = Salvage Value = 0

Substituting into Eqn. 5-1:

$$\therefore EUAC = (\$88{,}000)(0.1233) + 1{,}800 - 0\,(0.0833)$$

$$EUAC = \$12{,}650/\text{year}$$

Calculate NPW: Using Eqn 5-3,

$$NPW = PW_B - PW_C$$

but PW_B = 0, since there are no quantifiable benefits.

$$\therefore NPW = PW_C = IC + (pwf')\,[MO + UC] - (pwf)[S] \qquad \text{(Eqn. 5-5)}$$

where:

IC = Initial Construction Costs = \$88,000

MO = \$1,800/year as before

UC = 0 as before

S = 0 as before

Therefore, the present worth discount factors are:

$$pwf = \frac{1}{(1 + i)^n} = \frac{1}{(1 + 4\%)^{10}} = 0.6756$$

$$pwf' = \frac{(1 + i)^n - 1}{i\,(1 + i)^n} = \frac{(1 + 4\%)^{10} - 1}{4\%\,(1 + 4\%)^{10}} = 8.1109$$

Substituting into Eqn 5-5:

$$\therefore NPW = 88{,}000 + (8.1109)\,(1{,}800 + 0) - (0.6756)(0)$$

$$NPW = \$102{,}600$$

From the examples, the results for the same road design may be expressed in two ways:

- o A cost of \$12,650 a year for 10 years.
- o A discounted total present cost of \$102,600.

6.0 USER'S GUIDE

This chapter provides a user's manual or guide to the Surfacing Thickness Program (STP). It is intended that the user will use the Design Guide in the preceding chapters as a reference for more detailed information when assembling the appropriate input variables, particularly those for material characterization. However, some help screens are also included with the program to aid the designer as much as possible, as well as warning messages to indicate if values entered are out of range. This computer program may be run on IBM-compatible personal computers using MS-DOS. It requires 640k RAM. The monitor may be either monochrome or color.

Four files are required for the program to run:

STP.EXE	Contains the executable program
CHOICES.TXT	Contains pop-up menus
HELP.TXT	Contains the help screens
VEHICLES.TXT	Contains the array for the vehicle equivalency factors

The most current version of the program is Version 1.04 (August 1991). A previously released version was Version 1.02 (March 1990).

The rest of this section is organized as a series of notes that accompany the program menus and screens. General menus are first presented, followed by the aggregate-surfaced road design module, the earth road design module, and finally, the economic analysis module. The user is encouraged to refer to the preceding chapters as much as possible if guidelines are desired when entering a variable.

HELP SCREENS

The help screens provided in the program are stored in an accompanying file, HELP.TXT. The user may modify this file to suit their needs. Caution: There are three items that the user must be aware of:

1. Any line in the HELP.TXT file that begins with an asterisk (*) must not be modified. The program keys onto these lines so that the help screens will appear at the appropriate locations.

2. The HELP.TXT file must remain in ASCII, so only ASCII word processors such as PC-Write may be used to modify the file. In addition, other text editors such as Norton Commander, EDLIN or SideKick may be used. Word processors such as WordPerfect or WordStar may

not be used unless the file is saved in ASCII mode.

3. The HELP.TXT file has a maximum limit of 500 lines.

To determine if a file is in ASCII, type the following at the DOS prompt:

TYPE HELP.TXT

If the user can read this file on the monitor as it scrolls by, and there are no unusual symbols (such as smiling faces) present, then the file is in ASCII.

POP-UP MENUS

Choices for the pop-up menus are stored in the CHOICES.TXT file and may also be modified, with a text editor, and with the same cautions as for the HELP.TXT file above. Currently, two pop-up menus exist as illustrated later in this section:

1. Vehicle type and equivalency factors
2. Reliability factors

However, if the CHOICES.TXT file is modified, the corresponding VEHICLE.TXT file must also be modified. The VEHICLES.TXT file contains an array of equivalency factors that the program reads in sequential order. Therefore, if the order of vehicles or the equivalency factors in CHOICES.TXT are changed, a corresponding change must occur in VEHICLES.TXT. The user may also add vehicles to the list in both files. Caution: It must be noted that the format of this file cannot be changed, i.e., the first column must either be the vehicle number or the reliability factor. Refer to Chapter 2.0, Appendix B and Appendix C for background on the development of both the equivalency and reliability factors.

DATA FILES

Input data files (*.DAT) are not saved in ASCII--this is to prevent any possible corruption of the data file. However, saving the results to an output file is an option in the program, and the output is in ASCII. Three default output filenames are used:

AGG.OUT = Aggregate-surfaced road design result summary
EAR.OUT = Earth road design result summary
ECO.OUT = Economic analysis result

If an existing file with the above names are present in the current directory, they will be over-written. Therefore, the user should rename their files to prevent any loss of data. Since these files are

in ASCII, the user may also modify them with a text editor if desired.

```
USFS Surfacing Thickness Program - Version 1.04
```

```
This program was developed by ARE Inc - Engineering
Consultants as part of Contract No. 53-04H1-8-6230 for
the USDA - Forest Service.


                    Version 1.04 1991
```

```
Press any key to continue . . .
```

1. Type "STP" to start the program. This will be the first screen.

```
ACKNOWLEDGMENTS

The Surfacing Thickness Program
was funded by:
U.S. Department of Agriculture
Forest Service
```

```
The computer program is available on request with the understanding that
the U.S. Department of Agriculture cannot assure its accuracy,
completeness, reliability, or suitability for any other purpose than
that reported.  The recipient may not assert any proprietary rights
thereto nor represent it to anyone as other than a Government-produced
computer program.  For cost information, please write Peter Bolander,
USFS Region 6, P.O. Box 3623, Portland, OR 97208, (503) 326-3249 or John
Steward, Forest Service - USDA, 14th and Independence SW, 201 14th
Street S.W., Washington DC 20250 (202) 453-9448.
```

```
Press any key to continue . . .
```

1. This is the Acknowledgments screen. Note that there are 2 points of contact listed if the user wishes to obtain additional copies of the program.

```
USFS Surfacing Thickness Program

            MAIN MENU

    Aggregate Thickness Design
    Earth Thickness Design
    Cost (Economic) Analysis
    Regional Design Systems
    Exit to DOS

<F1>=Help.  Use arrow keys to select.
   <Esc> returns to previous menu
```

1. Use the arrow keys to highlight the module desired. Press <Enter> to make a selection. It is also possible to press the first letter, such as "A" to select "Aggregate Thickness Design".

2. Pressing <ESC> will always take you back to the previous screen at all times.

3. Press <F1> to pull up the help menu. The help menus will be screen specific, i.e., relate only to the current screens. The Help Screen for the Main Menu is shown on the next page. The user may modify help screens if desired through the HELP.TXT file. This has been explained previously.

4. All the above options in the Main Menu are discussed in preceding chapters of this design guide:

   Aggregate Thickness Design - Chapters 2, 3, 4
   Earth Thickness Design - Chapters 2, 3, 4
   Cost (Economic) Analysis - Chapter 5

5. The item "Regional Design System" is an option that is intended for future needs. Eventually, Region-specific design methods may be included as a part of a subroutine to this program. Currently, this feature has <u>not</u> yet been implemented.

```
                                                   <PgDn> for more
Aggregate Thickness Design - Design thickness of aggregate on aggregate-
                             surfaced road using traffic, soil strength
                             and seasonal data.

Earth Thickness Design     - Analyze rut depths calculated for a native-
                             surfaced road from user-defined traffic,
                             soil strengths (CBR) and seasonal data.

Cost (Economic) Analysis   - An economic analysis of different surfacing
                             alternatives using life-cycle costs.

Regional Design System     - This is a proposed customized design method
                             for region-specific criteria. This feature
                             has NOT yet been implemented. See your
                             Regional geotechnical engineer.

Exit to DOS                - This allows you to exit the STP program back
                             to the Disk Operating System (DOS). Pressing
                             <ESC> will also allow you to exit the
                             program.

        Press the ENTER key or the ESC key to exit help and continue
```

1. This is the Help screen for the main menu. All help screens will be of the same general format. Use the <PgDn> key to view additional pages.

2. All help screens may be modified by the user as explained in the previous section of this chapter.

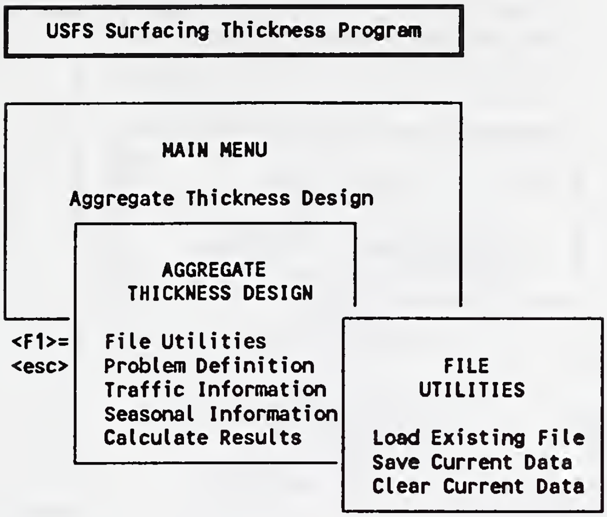
```
USFS Surfacing Thickness Program

MAIN MENU

Aggregate Thickness Design

AGGREGATE
THICKNESS DESIGN

<F1>=          File Utilities        select.
<esc>        Problem Definition
             Traffic Information
             Seasonal Information
             Calculate Results
```

1. This is the Aggregate Thickness menu. The user enters Traffic & Seasonal information and obtains the resultant design thickness in "Calculate Results."

2. Use arrow keys to highlight the option desired, or press first letter of each option.

3. Press <F1> to obtain a help screen.

4. Press <ESC> to go to previous menu.



1. This is the File Utilities screen.

2. When starting a new problem, the user can load an existing file and use/modify that data as required. Alternatively, the user can enter new data and then save the new problem using "Save Current Data." The data file saved is not in ASCII so as to protect the user from any possible data corruption.

3. "Clear Current Data" will remove all existing data inputs and return the user to the "Aggregate Thickness Menu" screen.

4. Press <F1> to obtain a help screen, <ESC> to exit to previous menu.

```
USFS Surfacing Thickness Program
```

```
RETRIEVE DATA FILE

Enter file name:  *.DAT

 To pick from list press enter
 (Or press <ESC>
 to ignore...
```

1. Data files may be saved using any format as long as they meet DOS requirements, i.e., not greater than 8 alphanumeric characters with a 3 character extension (e.g., XXXXXXXX.XXX). However, it is suggested that a ".DAT" extension be used to indicate a data file.

2. The "Save Current Data" screen is similar to this one.

3. If the user cannot remember an old file, pressing the [ENTER] key at the *.DAT field will bring up the following menu on the next page. The asterisk (*) is a wildcard character. Note that if the user requested a listing of all "*.DAT" files (i.e., data files with a .DAT extension) then only those files will be listed. To obtain a listing of <u>all</u> files in the current directory, type "*.*".

```
Select File
AGG.DAT
EARTH.DAT

        USFS Surfacing Thickness Program

                  MAIN MENU

          Aggregate Thickness Design

                 AGGREGATE
              THICKNESS DESIGN

<F1>=    File Utilities
<esc>    Problem Definition              FILE
         Traffic Information           UTILITIES
         Seasonal Information
         Calculate Results          Load Existing File
                                    Save Current Data
                                    Clear Current Data
```

1. Use arrow keys to highlight the desired file and press <Enter> to retrieve.

2. Note that only files with a .DAT extension are listed in this case.

```
USFS Surfacing Thickness Program

MAIN MENU

Aggregate Thickness Design

AGGREGATE
THICKNESS DESIGN

PROBLEM DEFINITION

PROBLEM NUMBER        Road 1A

PROBLEM DESCRIPTION
Road 1A, Sample NF, Oregon
MP 3.4 to MP 3.6
```

1. Type in problem numbers and description in fields. Press <ESC> when done.

2. To save the data entered here, the user has to go to the File Utilities Menu and select "Save Current Data." (See previous page.) To retrieve the data, select "Load Existing File" from the File Utilities menu.

3. Press <F1> to obtain a help screen.

4. Press <F1> <u>twice</u> to obtain the key definitions.

```
                    ┤ TRAFFIC INFORMATION ├

 Use 1) Timber Volume Method or 2) Vehicle Type Method.
 Press F10 to save and exit.
  1a.  Timber Volume          :  10.00  MMBF
  1b.  Conversion Factor      :   5000  BF for 1 Std
  1c.  % Non-Log Truck Traffic :    25     Log Truck
            TOTAL 18K ESALS -->  11412
                  Equivalency
 Veh. No Vehicle Type     Factor    Passes    18-Kip ESAL

                          0.000        0            0
                          0.000        0            0
                          0.000        0            0
                          0.000        0            0
                          0.000        0            0
                          0.000        0            0
                          0.000        0            0
                          0.000        0            0
                          0.000        0            0
                          0.000        0            0
                           TOTAL 18K ESALS -->

  3.   Reliability Factor :    1.44 Aggregate Design Only
```

1. The traffic information may be entered in 2 ways; either through timber volume or specifying actual vehicle data. Press <F1> to bring up a help screen for more information.

2. If timber volume calculations are performed, the user will not be able to enter individual vehicle information.

3. The timber volume calculation is shown below as:

   (Timber Volume/Conversion Factor)*(1 + % Non-log Truck)*(EF)*(F_R)

   i.e., (10 MMBF/5 MBF) (1.25) (3.17) (1.44) = 11,412 18^K ESALs

   The default conversions are 5 MBF to 1 standard log truck, and 25% for the non-log truck factor.

4. Pressing <F2> in the Reliability Factor field will bring up the "Reliability Factor" Pop-Up, as shown on page 91. This option is available <u>only</u> for aggregate-surfaced road design. The default is 1.0, which is equivalent to a 50% reliability level.

5. Press <F1> <u>twice</u> to bring up key definitions.

```
                    TRAFFIC INFORMATION

 Use 1) Timber Volume Method or 2) Vehicle Type Method.
 Press F10 to save and exit.
  1a.  Timber Volume          :   0.00  MMBF
  1b.  Conversion Factor      :   5000  BF for 1 Std
  1c.  % Non-Log Truck Traffic :    25     Log Truck
              TOTAL 18K ESALS -->
                     Equivalency
 Veh. No Vehicle Type     Factor   Passes   18-Kip ESAL

  3  Empty Log Truck     0.760    4000          4378
  8  Standard Log Truck  3.170    2000          9130
 40  Washington 208 w/t 16.970       2            49
 13  Off Hwy Log Truck   5.580    2000         16070
                         0.000       0             0
                         0.000       0             0
                         0.000       0             0
                         0.000       0             0
                         0.000       0             0
                         0.000       0             0
                       TOTAL 18K ESALS -->     29626

  3.    Reliability Factor :    1.44 Aggregate Design Only
```

1. Zero <u>must</u> be entered in the first field (timber volume) before the user can select and/or enter specific vehicles separately.

2. Press <F2> when the cursor is in the "Vehicle Type" field to bring up the appropriate pop-up menu (see next page). Then select the appropriate vehicle by using the cursor to highlight the desired vehicle, then <Enter> to select. To enter a vehicle not listed in the pop-up, enter a zero in the vehicle number column.

3. Pressing <F2> when the cursor is in the "Reliability Factor" field will bring up the "Reliability Factor" Pop-Up, as shown on page 91.

4. The "Total 18^k ESALs" shown in either option will include the effects of the Reliability Factor. Note that this algorithm was developed for a total 18 kip ESALs between 200 and 50,000. Values outside this range will result in a warning message (see page 92).

5. Pressing <F1> will bring up a help screen. Press <F1> <u>twice</u> to list the key definitions.

6. To edit the pop-up menus, the user may modify a file called <u>CHOICES.TXT</u> with a text editor. This file <u>must</u> be edited in ASCII format. This has been previously discussed.

Veh. No.	Description of Vehicle	Equivalency Factor	Tire Pressure (psi)	Comment
1	18-Kip ESAL	1.00	80	
2	Empty Log Truck	0.29	64,25	CTI-10k steer,16k drive
3	Empty Log Truck	0.76	80	Total weight 26 kips
4	Empty Log Truck	1.00	90	
5	Standard Log Truck	1.07	50	Total weight 80 kips
6	Standard Log Truck	1.28	64,52,52	CTI-10k steer,35k dr & tr
7	Standard Log Truck	1.95	70	Total weight 80 kips
8	Standard Log Truck	3.17	80	Total weight 80 kips
9	Standard Log Truck	4.16	90	
10	Standard Log Truck	5.30	100	Total weight 80 kips
11	Off Hwy Log Truck	1.90	50	Total Weight 108 Kips
12	Off Hwy Log Truck	3.43	70	Total Weight 108 Kips
13	Off Hwy Log Truck	5.58	80	Total Weight 108 Kips
14	Off Hwy Log Truck	9.33	100	Total Weight 108 Kips
15	Dump Truck	0.68	50	46,000 GVW
16	Dump Truck	1.31	70	46,000 GVW
17	Dump Truck	2.01	80	46,000 GVW
18	Dump Truck	3.35	100	46,000 GVW

Vehicle Type Pop-up

Cursor keys scroll, ENTER selects and ESC exits choice menu

1. This is the first page of the Vehicle Type pop-up menu. Press <F2> at the "Vehicle Type" field to get this screen. Use arrow keys to highlight selection, and <Enter> to select.

2. The user may add to or modify this pop-up by using an ASCII text editor to modify the CHOICES.TXT file in the current directory. However, the user must also make sure that the corresponding changes are performed to the VEHICLES.TXT file as well to ensure program integrity. Note: It is important that these *.TXT files remain in ASCII.

3. Note that two triple axle trucks have been included in the pop-up. The equivalency factors determined for these vehicles are preliminary in nature and caution should be used when including them in any analyses. It is preferable that users obtain more precise values for their needs.

Reliability Level Pop-up		
Reliability Factor	TSL	Reliability Level
1.00	D	50%
1.44	C	70%
2.32	B	90%

Cursor keys scroll, ENTER selects and ESC exits choice menu

1. Press <F2> at the "Reliability Factor" field to obtain this pop-up.
2. Use arrow keys to scroll to desired factor and hit <Enter> to make selection. This value will now be entered in the field.

```
Warning:       The total 18-kip ESALs entered is either greater
               than 50,000 or less than 200.  The program will
               calculate the results based on the maximum or
               minimum allowable number.

Discussion :   The algorithm used for this program was based
               on a maximum of 50,000 total 18 kip ESALs and a
               minimum of 200 18-kip ESALs.
               Traffic greater than 50,000 may have variables
               other than rutting dictating the structural thickness.
               These variables could be the timing and method of road
               maintenance or the material properties of the aggregate

Recommendations: 1) Reduce the analysis period to keep the design traffic
                    less than 50,000 or more than 200 18-kip ESALs.
                 2) Evaluate the sensitivity of your situation
                    to traffic as shown in Figure 22 of the
                    Aggregate Design Guide.


            <Press any key to Continue>
```

1. This is the warning message that occurs when the total number of 18-kip ESALs entered is:

   a. Less than 200
   b. Greater than 50,000.

USFS Surfacing Thickness Program

SEASONAL INFORMATION - AGGREGATE DESIGN

	ESTIMATED % TRAFFIC	SUBGRADE CBR	SURFACE CBR
SEASON 1	20.0	3.0	20.0
SEASON 2	80.0	15.0	60.0
SEASON 3	0.0	0.0	0.0
SEASON 4	0.0	0.0	0.0
TOTAL (%)	100.0		

1. This is the Seasonal Information screen.

2. After the user enters the subgrade CBR, the surface CBR is automatically calculated (Surface CBR = 4 x Subgrade CBR). However, the user may manually over-ride this value, if desired.

3. If surface CBR is more than four times subgrade CBR, a warning message will pop-up (see next page). After the user has read the warning, pressing any key will return the user to the "Seasonal Information" screen. If the CBRs are not changed, the program will calculate aggregate thickness based on the data entered, not the data calculated.

4. Press <F1> to obtain a help screen.

5. Press <F1> twice to obtain key definitions.

```
USFS Surfacing Thickness Program
```

```
WARNING! Algorithm was developed for
surface CBR not less than 20 and not
greater than 4 times subgrade CBR.
In addition, subgrade CBR is assumed
to be greater than 3. Aggregate
thickness will be calculated based on
the data you entered. Press <F1> Help
for further explanation.
    <Press any key to Continue>
```

1. This is the warning message that occurs when:
   a. Surface CBR > 4 x Subgrade CBR
   b. Subgrade CBR < 3
   c. Surface CBR < 20

2. After the user has read the warning, pressing any key will return the user to the "Seasonal Information" screen. If the CBRs are not changed, the program will ignore the $C_1 > 4C_2$ ratio and calculate aggregate thickness based on the data entered.

```
┤CALCULATE RESULTS - AGGREGATE DESIGN├

  PROBLEM NUMBER      Road 1A

  PROBLEM DESCRIPTION
  Road 1A, Sample NF, Oregon
  MP 3.4 to MP 3.6

  Allowable Rut Depth (inches)  . .         2.0
  Aggregate Loss (inches) . . . . .         0.0
   (typically 1 inch for 10 MMBF)
  Structural Thickness (inches) . .        11.5
  Total Aggregate Thickness (inches):      11.5
  Practical Min. Thickness  (inches):       4.0
                  Damage Ratios
  Season 1  Season 2  Season 3  Season 4    TOTAL
  --------  --------  --------  --------    -----
      0.97      0.01      0.00      0.00     0.98
  Press <Alt-P> for Printer or <Alt-F> for File!
```

1. This is the results summary for the aggregate design subroutine.

2. The user may enter a value in the "Allowable Rut Depth" and "Aggregate Loss" fields.

3. The program calculates "Structural Thickness" based on the "Allowable Rut Depth" shown here as well as the "Traffic and Seasonal Information" previously entered. The "Aggregate Loss" may be added to the "Structural Thickness" for a "Total Aggregate Thickness." The user should round off the results as appropriate.

4. A warning message will occur if the rut depth exceeds half of the aggregate structural thickness (see next page).

5. Seasonal damage ratios are displayed and summed for the user. The program has selected a "Structural Thickness" so that the resulting "Total Damage Ratio" is $\leq$ 1.0.

6. Press <ALT-P> to print. The printer must be connected to a parallel port (LPT1:).

7. Press <ALT-F> to print the output to a file. The default filename is AGG.OUT. Successive outputs will over-write any existing files, so the user must rename files if you wish to save it.

<u>TIP</u>
If printing problems result with the <ALT-P> option, use <ALT-F> instead. To print the AGG.OUT file, type the following at the DOS prompt: **TYPE AGG.OUT>PRN**

```
WARNING!  Allowable rut depth should be
          between 1 and 6 inches.


          <Press any key to Continue>
```

```
WARNING! Rut Depth exceeds 1/2 structural thickness.
         This may represent a bearing capacity failure
         Reduce the allowable rut depth to less than
         1/2 the structural thickness.  Also verify
         traffic information.

              <Press any key to continue>
```

1. The first screen is the warning message that occurs if rut depth is greater than half of the aggregate structural thickness. Check your inputs if this occurs.

2. The second screen is the warning message that occurs if rut depth is greater than half of the aggregate structural thickness. Check your inputs if this occurs.

USFS SURFACING THICKNESS PROGRAM
Aggregate Design

```
Problem Number       : Road 1A
Problem Description  : Road 1A, Sample NF, Oregon
                       MP 3.4 to MP 3.6
Date of Analysis     : 8/15/1991
Filename             : AGG.DAT
```

SUMMARY OF INPUT AND RESULTS

Vehicle Type	Equivalency Factor	Actual Passes	No. Passes of 18K ESALS
3 Empty Log Truck	0.76	4000	4378
8 Standard Log Truck	3.17	2000	9130
40 Washington 208 w/t	16.97	2	49
13 Off Hwy Log Truck	5.58	2000	16070
	0.00	0	0
	0.00	0	0
	0.00	0	0
	0.00	0	0
	0.00	0	0
	0.00	0	0
		Total 18K ESALS =	29626

Reliability Factor : 1.44

	Estimated Traffic	Surface CBR	Subgrade CBR	Damage Ratios
Season 1	20.0	20	3	0.97
Season 2	80.0	60	15	0.01
Season 3	0.0	0	0	0.00
Season 4	0.0	0	0	0.00
TOTAL =	100.0 Percent			0.98

```
Allowable Rut Depth             :   2.0 inches

Aggregate Loss                  :   0.0 inches
Structural Thickness Required   :  11.5 inches
                                  -------
Total Aggregate Thickness Req'd :  11.5 inches
```

1. This is a sample AGG.OUT file.

```
                    TRAFFIC INFORMATION

Use 1) Timber Volume Method or 2) Vehicle Type Method.

 1a.  Timber Volume          :  10.00  MMBF
 1b.  Conversion Factor      :   5000  BF for 1 Std
 1c.  % Non-Log Truck Traffic :    25      Log Truck
              TOTAL 18K ESALS -->  7925
                        Equivalency
Veh. No Vehicle Type       Factor   Passes   18-Kip ESAL

                           0.000       0             0
                           0.000       0             0
                           0.000       0             0
                           0.000       0             0
                           0.000       0             0
                           0.000       0             0
                           0.000       0             0
                           0.000       0             0
                           0.000       0             0
                           0.000       0             0
                            TOTAL  18K ESALS -->
```

1. This is the Traffic Information screen for the Earth Design. The only difference from the aggregate-surfaced road design is that no reliability factors are used in the analysis.

2. Press <F1> to get a help screen.

USFS Surfacing Thickness Program

SEASONAL INFORMATION - EARTH DESIGN

	ESTIMATED % TRAFFIC	COMPACTED CBR	UNCOMPACTED CBR
SEASON 1	75.0	10.0	6.0
SEASON 2	25.0	5.0	3.0
TOTAL (%)	100.0		

1. This is the Seasonal Factors menu for the Earth Design. Note that only two seasons are allowed.

2. Also, the compacted CBR should not be greater than two times the uncompacted CBR or a warning message will occur. Press <F1> (Help) for guidelines on the selection of appropriate CBRs.

```
┌┤RESULTS SUMMARY - EARTH DESIGN├──────────────────────┐
│                                                       │
│   PROBLEM NUMBER      Road 2A                         │
│                                                       │
│   PROBLEM DESCRIPTION                                 │
│   Road 2A, Sample NF, Oregon                          │
│   MP 1.2 to MP 1.3                                    │
│                                                       │
│                                                       │
│   Compacted Thickness (inches) . . . .    6.0         │
│   Rut Depth (inches)    . . . . . . . .  10.6         │
│                                                       │
│                  Damage Ratios                        │
│   Season 1         Season 2          Total            │
│   --------         --------         -------           │
│    0.09             0.88             0.96             │
│                                                       │
│   Press <Alt-P> for Printer or <Alt-F> for File!      │
└───────────────────────────────────────────────────────┘
```

1. This is the results summary for the earth road design subroutine.

2. Press <ALT-P> to print. The printer must be connected to a parallel port (LPT1:).

3. Press <ALT-F> to print the output to a file. The filename is EAR.OUT. Successive outputs will over-write this file, so the user must rename the file if they wish to save it.

TIP

If printing problems result with the <ALT-P> option, use <ALT-F> instead. To print the EAR.OUT file, type the following at the DOS prompt: **TYPE EAR.OUT>PRN**

```
                    USFS SURFACING THICKNESS PROGRAM
                              Earth Design

     Problem Number      : Road 2A
     Problem Description : Road 2A, Sample NF, Oregon
                           MP 1.2 to MP 1.3
     Date of Analysis    : 8/15/1991
     Filename            : EARTH.DAT



                     SUMMARY OF INPUT AND RESULTS

     Timber Volume             :        10 MMBF
     Conversion Factor         :      5000 BF for 1 Std Log Truck
     Percent Non-Truck Traffic :        25

     Total 18K ESALS           :      7925


     Reliability Factor  :  1.00


                 Estimated   Compacted  Uncompacted    Damage
                  Traffic       CBR         CBR        Ratios
                 ---------    -------    --------      ------

      Season 1      75.0        10           6          0.09
      Season 2      25.0         5           3          0.88
                 ---------                             ------
          TOTAL =  100.0  Percent                       0.96


      Compacted Thickness (inches) . . . .   6.0
      Rut Depth (inches)    . . . . . . . .  10.6
```

1. This is a sample EAR.OUT file.

```
USFS Surfacing Thickness Program

MAIN MENU

Aggregate Thickness Design
Earth Thickness Design
Cost (Economic) Analysis

        COST (ECONOMIC)
<F1>=       ANALYSIS          select.
<esc>
          File Utilities
          Problem Definition
          Calculate Results
```

1. This is the Economic Analysis menu.

2. The File Utilities and Problem Definition are similar to those for the Aggregate Thickness Design. See pages 84 through 87.

```
┤ECONOMIC ANALYSIS├
  Physical Geometry            Surfacing Construction Costs

Length (feet)       600                       Mat'l #1   Mat'l #2
Top Width (feet)   12.0  Thickness (inches)     5.0        3.0
Turnout Factor/              Volume (CY)      144.4       86.7
Curve Widening      1.3    Unit Cost ($/CY)   10.00      15.00
                                              ______     ______
                         Total Surfacing
                               Costs ($)    1444.44    1300.00

           Subgrade Prep. Add'l Cost ($)      2000.00
           Total Maintenance Costs ($/year)    500.00
           Total Operational Costs ($/year)    200.00
           Salvage Value ($)                     0.00
           Interest Rate (percent)               4.00
           Analysis Period (years)                 10
    Equivalent Uniform Annual Cost ($/year)   1284.95
                        Net Present Worth ($) 10422.07

         Press <Alt-P> for Printer or <Alt-F> for File!
```

1. This is the Economic Analysis screen.

2. The default for the "Turnout/Curve Widening Factor" is 1.30. When no turnouts are present, enter 1.0. <u>DO NOT ENTER ZERO!</u>

3. The program will calculate the surfacing volumes for Materials 1 and 2 based on the physical geometry information. The initial "Surfacing Construction Cost" is calculated based on unit costs entered by the user. In addition, the program allows the user to enter an initial "Subgrade Preparation" cost if appropriate, as well as uniform annual maintenance and operation costs. Finally, given an "Interest Rate" and "Analysis Period", both the "Equivalent Uniform Annual Cost" and "Net Present Worth" are calculated. The defaults for the interest rate and analysis period are 4% and 10 years, respectively.

4. Press <ALT-P> to print. The printer must be connected to a parallel port (LPT1:).

5. Press <ALT-F> to print the output to a file. The filename is ECO.OUT. Successive outputs will over-write any existing file, so the user must rename these existing files if they wish to save them.

<u>TIP</u>

If printing problems result with the <ALT-P> option, use <ALT-F> instead. To print the ECO.OUT file, type the following at the DOS prompt: **TYPE ECO.OUT>PRN**

```
                    USFS SURFACING THICKNESS PROGRAM
                           Economic Analysis

Problem Number      : Road 2A
Problem Description : Road 2A, Sample NF, Oregon
                      MP 1.2 to MP 1.3
Date of Analysis    : 8/15/1991
Filename            : EARTH.DAT


                     SUMMARY OF INPUT AND RESULTS


Physical Geometry

Length (feet)          600
Top Width (feet)      12.0
Turnout Factor /
Curve Widening         1.3


Surfacing Construction Costs

                           Mat'l #1          Mat'l #2
Thickness (inches)           5.0               3.0
Volume (CY)                144.4              86.7
Unit cost ($/CY)           10.00             15.00
                          --------------------------
Total Surfacing Cost ($)  1444.44           1300.00


Subgrade Preparation Additional Cost ($)   2000.00
Total Maintenance Cost ($/year)             500.00
Total Operational Cost ($/year)             200.00
Interest Rate (percent)                       4.00
Analysis Period (years)                         10


Equivalent Uniform Annual Cost ($/year)    1284.95
Net Present Worth ($)                     10422.07
```

1. This is a sample ECO.OUT file.

APPENDIX A
GLOSSARY OF TERMS

Aggregate-Surfaced Road - road that has an unbound aggregate material as the surface course.

Analysis Period - the period of time (usually years) for which the economic analysis is to be made.

Base Course - the layer or layers of specified or selected material of designed thickness placed on a subbase or a subgrade to support a surface course.

CBR - California Bearing Ratio. A test for determining the strength and supporting power of disturbed soils as recompacted under standard procedures.

Discount Rate (Interest Rate) - a percentage figure representing the rate of interest money can be assumed to earn over the period of time under analysis.

Earth Road - road that consists of the native soil with the top portion compacted so as to withstand traffic loads.

Equivalent Single Axle Load (ESAL) -a mixed combination of axle loads and axle configurations is converted to an equivalent 18,000-pound single axle load. These are summed over the analysis period.

Equivalent Single Wheel Load (ESWL) - the load on a <u>single</u> tire that will cause an equal magnitude of a preselected parameter (eg. deflection) as that resulting from a multiple-wheel load at the same location within the pavement structure.

Equivalency Factor - a numerical factor that expresses the relationship of a given axle load to another axle load in terms of their effect on the serviceability of a pavement structure. In this Guide all axle loads are equated in terms of the equivalent number of repetitions of an 18-kip single axle.

Equivalent Uniform Annual Cost (EUAC) - a uniform annual cost (or benefit) that is the equivalent, spread over the entire period of analysis, of all costs or disbursements incurred (or benefits received) on a project.

Flexible Pavement - an asphalt pavement structure which maintains intimate contact with and distributes loads to the subgrade and depends on aggregate interlock, particle friction, and cohesion for stability.

Life Cycle Costs - all costs and benefits that are involved in the provisions of a roadway during its complete life cycle. It includes construction costs, maintenance and rehabilitation costs, user costs, etc.

Low-Volume Road - a roadway generally subjected to low levels of traffic; in this Guide, structural design is based on a range of 18-kip ESAL's from 50,000 to 1,000,000 for flexible and rigid pavement, and from 1,000 to 50,000 for aggregate-surfaced roads.

Maintenance - the preservation of the entire roadway, including surface, shoulders, road sides, structures, and such traffic control devices as are necessary for its safe and efficient utilization.

Net Present Worth (NPW) - the net cumulative present worth of a series of costs and benefits stretching over time.

Pavement Performance - the trend of serviceability with load applications.

Pavement Rehabilitation - work undertaken to extend the service life of a roadway. This includes placement of additional surfacing material and/or other work necessary to return an existing roadway to a condition of structural or functional adequacy. This could include the complete removal and replacement of the pavement structure.

Pavement Structure - a combination of subbase, base course, and surface course placed on a subgrade to support the traffic load and distribute it to the roadbed.

Performance Period - the period of time that an initially constructed or rehabilitated pavement structure will last (perform) before reaching its terminal serviceability; this is also referred to as the "design period."

Prepared Roadbed - in-place roadbed soils compacted or stabilized according to provisions of applicable specifications.

Present Value (PV) or Present Worth (PW) - an economic concept that represents the translation of specified amounts of costs or benefits occurring in different time periods into a single amount at a single instant (usually the present).

R-Value - the Resistance value of the soil as determined through the Hveem stabilometer method. The R-value value ranges from 0 (liquid) to 100 (infinitely rigid solid).

Resilient Modulus - a measure of the modulus of elasticity of roadbed soil or other pavement material.

Roadbed - the graded portion between top and side slopes, prepared as a foundation for the pavement structure.

Roadbed Material - the material below the subgrade in cuts and embankments and in embankment foundations, extending to such depth as affects the support of the pavement structure.

Running Surface - the surface of the road upon which the traffic passes.

Salvage Value - the value of a roadway remaining at the end of the study or analysis period.

Selected Material - a suitable native material obtained from a specified source such as a particular roadway cut or borrow area, of a suitable material having specified characteristics to be used for a specific purpose.

Serviceability - the ability of a pavement to serve its intended function at any particular time.

Single Axle Load - the total load transmitted by all wheels of a single axle extending the full width of the vehicle.

Subbase - the layer or layers of specified or selected material of designed thickness placed on subgrade to support a base course (or in the case of rigid pavements, the portland cement concrete slab).

Subgrade - the top surface of a roadbed upon which the pavement structure and shoulders are constructed.

Surface Course - one or more layers of a pavement structure designed to accommodate the traffic load, the top layer of which resists skidding, traffic abrasion, and the disintegrating effects of climate.

Tandem Axle Load - the total load transmitted to the road by two consecutive axles extending across the full width of the vehicle.

APPENDIX B
EQUIVALENCY FACTORS

As described in Section 2.3, the standard axle type selected was the 18-kip equivalent single-axle load, with a tire pressure of 80 psi. The standard axle has an equivalency factor of 1.0. The design algorithm shown below was used to calculate equivalency factors for other axle types and configurations.

$$RD = 0.1741 \left(\frac{P_k^{0.4704} \, t_p^{0.5695} \, R^{0.2476}}{(\log t)^{2.002} \, C_1^{0.9335} \, C_2^{0.2848}} \right) \qquad \text{(Eqn. 3-1)}$$

where:

RD	=	Rut depth, in.
P_k	=	Equivalent single-wheel load (ESWL), kips
t_p	=	Tire Pressure, psi
t	=	Thickness of top layer, in.
R	=	Repetitions of load or passes
C_1	=	CBR of top layer
C_2	=	CBR of bottom layer

Note that P_k is the equivalent single-wheel load (ESWL). As defined by Yoder and Witczak[1], an ESWL "...is the load on a single tire that will cause an equal magnitude of a preselected parameter (such as deflection, stress or strain) at a given location within a specific pavement system to that resulting from a multiple-wheel load at the same location within the pavement structure." The Corps of Engineers[2] has developed a series of curves to calculate the ESWL as a percentage of the axle load. For a single axle-dual wheel load, the ESWL ranged from 31 -53% of the total axle load, and for the tandem axle, dual wheel load, it ranged from 17 - 35%. For a single-axle, single wheel (such as the steering axle of a truck) load, the range is 52 - 63%. The ranges are due to different aggregate thicknesses. For this design guide, the appropriate factor for an aggregate thickness of 15 inches was used. Therefore, the single axle, dual wheel conversion factor is 48%, for the tandem axle is 29%, and for the single axle, single wheel, it is 57%.

To calculate equivalency factors for the various loads and wheel configurations we will assume a typical pavement, repetitions and tire pressure, and determine the rut resulting from an 18k ESAL. Using this rut depth, the number of repetitions for other axle loads and wheel configurations are calculated for

---

[1] Yoder and Witczak, Op. Cit.

[2] Chou, Y.T., "Design Criteria for Aggregate-Surfaced Roads and Airfields," Technical Report GL-89-5, U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, 1989.

the same pavement and tire pressure. The ratio of passes for the 18-kip to that for another load and wheel configuration then becomes the equivalency factor for other load and wheel configurations.

To calculate the rut depth for the standard axle (i.e. 18-kip ESAL) at a tire pressure of 80 psi, the following steps are performed:

1. Convert 18^k ESAL to ESWL. For a single-axle dual wheel load, the conversion factor is 0.48. Therefore,

   $$\begin{aligned} ESWL_{18} &= (18 \text{ kips})\ (48\%) \\ &= 8.64 \text{ kips} \end{aligned}$$

2. Assume R = 10,000 passes of the 18-kip ESALs.
3. Assume t = 4" of aggregate thickness.
4. Assume $C_1 = 40$ & $C_2 = 10$
5. Tire pressure = 80 psi
6. The rut depth for the standard vehicle is then calculated as:

$$RD_{18} = 0.1741 \left(\frac{P_k^{0.4704}\ t_p^{0.5695}\ (10{,}000)^{0.2476}}{(\log 4")^{2.002}\ (40)^{0.9335}\ (10)^{0.2848}} \right)$$

$$= 0.0780 \quad (P_k^{0.4704}\ t_p^{0.5695})$$

$$= 0.0780 \quad ((8.64 \text{ kips})^{0.4704}\ (80 \text{ psi})^{0.5695})$$

$$\underline{RD_{18} = 2.61 \text{ inches}}$$

<u>Equivalency Factors</u>: The following steps describe the calculation of the equivalency factor for another vehicle. As an example, assume a standard log truck, with 2 tandem axles and a steering axle. The tandem axle load is 35 kips, the steering axle is a single wheel 10-kip single axle, and tire pressures are 100 psi.

1. First, obtain the ESWLs for both axles.

$$ESWL_{35} = (29\%)\ (35 \text{ kips}) = 10.15 \text{ kips}$$
$$ESWL_{10} = (57\%)\ (10 \text{ kips}) = 5.70 \text{ kips}$$

2. Now calculate the number of repetitions for each axle given a rut depth of 2.61 inches and using the <u>same</u> assumptions as before for t, C_1 and C_2. Using Eqn. 3-1:

$$RD = 0.1741 \frac{P_k^{0.4704} \, t_p^{0.5695} \, R^{0.2476}}{(\log t)^{2.002} \, C_1^{0.9335} \, C_2^{0.2848}} \qquad \text{(Eqn. 3-1)}$$

Substituting:

$$2.61" = \frac{0.1741 \, (10.15 \text{ kips})^{0.4704} \, (100 \text{ psi})^{0.5695} \, R_{35}^{0.2476}}{(\log 4)^{2.002} \, (40)^{0.9335} \, (10)^{0.2848}}$$

Solving for R_{35}: R_{35} = 4,418 ESALs

Similarly for R_{10}: R_{10} = 13,223 ESALs

3. The equivalency factor is the ratio of the number of repetitions of the standard axle to the number of repetitions of the actual axle.

For the 35-kip tandem axle, the equivalency factor is:

$$EF_{35} = \frac{10{,}000}{4{,}418} = 2.26 \qquad \text{(See Figure 15)}$$

For the 10-kip single axle, the equivalency factor is:

$$EF_{10} = \frac{10{,}000}{13{,}223} = 0.76 \qquad \text{(See Figure 15)}$$

Therefore, the equivalency factor for the truck is:

$$EF_{truck} = EF_{35} \text{ (2 tandem axles)} + EF_{10} \text{ (1 steering axle)}$$
$$= 2.26 \, (2) + 0.76 \, (1)$$
$$EF_{truck} = \underline{\underline{5.28}}$$

Figures 12, 13, 14, 15 and 16 in Chapter 2 summarize equivalency factors for a variety of load and axle configurations as well as for tire pressures of 25, 50, 70, 80 and 100 psi, respectively. Note that there may be small differences in the equivalency factors. This is due to round-off errors. Figure 17 illustrates equivalency factors for triple axles on a flexible pavement with a P_t of 2.0. This figure is derived from the AASHTO Guide.

APPENDIX C
RELIABILITY LEVELS

AASHTO describes the concept of reliability as follows:

> "The reliability of a pavement design performance process is the probability that a pavement section designed using the process will perform satisfactorily over the traffic and environmental conditions for the design period."

The design algorithm used in this guide to predict rut depth is a deterministic model. It represents not necessarily the best fit of all the data, but instead a "good fit" as indicated by the error and correlation values. The reliability of a facility can be determined in terms of the probability that a given rut depth will occur under given circumstances. It is a statistical measure of the probability that a pavement will perform in a given manner during its life. To address the concept of reliability in this design guide, stochastic models were developed by Barber et al.[1] Much of this discussion is excerpted from their report. The expected value E[RD] and variance V[RD] models for the rut depth equation are shown in Figure C.1.

<u>Determination of Reliability</u>: Each variable in the two models is used in terms of its respective mean and variance and in turn an expected value and variance of rut depth is determined. As has been previously stated, reliability as defined and used in this guide is the probability that the rut depth will not exceed some predetermined value subject to conditions that are expressed by the independent variables.

If the rut depth is normally distributed, the reliability statistic P used to determine the reliability R that the rut depth will not exceed some maximum value RD_A can be expressed by:

$$P = \frac{RD_A - E(RD)}{\sqrt{V(RD)}} \qquad \text{(Eqn. C-1)}$$

where:

E(RD)	=	expected value of the rut depth
V(RD)	=	variance of the rut depth

---

[1]Barber, V.C., E.C. Odom and R.W. Patrick, "The Deterioration and Reliability of Pavements," Technical Report S-78-8, U.S. Army Engineers Waterways Experiment Station, Vicksburg, Miss., July 1978.

$$RD = \frac{0.1741\, P_K^{0.4707}\, t_P^{0.5695}\, R^{0.2476}}{(\log t)^{2.002}\, C_1^{0.9335}\, C_2^{0.2848}} = Q \text{ in the following equations.}$$

$$E[RD] = Q\left\{1 + 0.5\left(\frac{0.8695}{\mu_t^2 \log \mu_t}\left\{\frac{1.3038}{\log \mu_t} + 1\right\}\sigma_t^2 - \frac{0.2491\sigma_{PK}^2}{\mu_{PK}^2}\right.\right.$$

$$\left.\left. - \frac{0.2452\sigma_{tp}^2}{\mu_{tp}^2} - \frac{0.1863\sigma_R^2}{\mu_R^2} + \frac{1.8049\sigma_{C1}^2}{\mu_{C1}^2} + \frac{0.3659\sigma_{C2}^2}{\mu_{C2}^2}\right)\right\}$$

$$V[RD] = Q^2\left\{\left(\frac{0.4707\sigma_{Pk}}{\mu_{Pk}}\right)^2 + \left(\frac{0.5695\sigma_{tp}}{\mu_{tp}}\right)^2 + \left(\frac{0.2476\sigma_R}{\mu_R}\right)^2 + \left(\frac{-0.8695\sigma_t}{\mu_t \log \mu_t}\right)^2\right.$$

$$\left. + \left(\frac{-0.9335\sigma_{C1}}{\mu_{C1}}\right)^2 + \left(\frac{-0.2848\sigma_{C2}}{\mu_{C2}}\right)^2\right\}$$

$$- 0.25\ Q^2\left\{\left[\frac{0.8695}{\mu_t^2 \log \mu_t}\left(\frac{1.3038}{\log \mu_t} + 1\right)\sigma_t^2\right]^2\right.$$

$$+ \left[\frac{-0.2491}{\mu_P^2}\sigma_P^2\right]^2 + \left[\frac{-0.2452}{\mu_{tp}^2}\sigma_{tp}^2\right]^2 + \left[\frac{-0.1863}{\mu_R^2}\sigma_R^2\right]^2$$

$$\left. + \left[\frac{1.8049}{\mu_{C1}^2}\sigma_{C1}^2\right]^2 + \left[\frac{0.3659}{\mu_{C2}^2}\sigma_{C2}^2\right]^2\right\}$$

Figure C.1 Gravel Surfaced facility expected value variance, and rutting models

where:

μ_i = mean or average of variable i

σ_i = standard deviation of variable i

σ_i^2 = variance of variable i

i = t (aggregate thickness)

t_p (tire pressure)

P_k (ESWL)

R (No. of repetitions)

C_1 (Aggregate CBR)

C_2 (Subgrade CBR)

E(RD) = expected value of the rut depth

V(RD) = variance of the rut depth

Figure C.1 Gravel Surfaced facility expected value variance, and rutting models (Continued)

Figure C.2 illustrates a standard normal distribution curve and the parameters utilized to compute the reliability statistic P. In order to determine reliability R from Figure C.3 or, that is, the area under the distribution curve defined by E(RD) and V(RD) and to the left of maximum rut depth RD_A, enter the table with the value of P determined previously and read the area under the distribution curve that is the reliability. As an example, assume the following values:

$$RD_A = 3 \text{ in.}$$
$$E(RD) = 2 \text{ in.}$$
$$V(RD) = 1 \text{ in.}$$

then $P = \frac{RD_A - E(RD)}{\sqrt{V(RD)}} = \frac{3 - 2}{1} = \frac{1}{1} = 1$. If Figure C.3 is entered with a value of 1 in the left-hand column interpolation is not necessary. It can immediately be seen that R = 0.8413, which means that there is a probability of 0.8413 that the rut depth will not exceed a predetermined maximum value of 3 inches. Figure C.3 is typical of similar tables found in most statistics textbooks.

Figure C.4 summarizes the reliability levels (%) obtained for different traffic levels and aggregate thicknesses. The variables used to obtain these numbers are shown in the bottom portion of Figure C.4. Note that the standard deviations used for tire pressure and material CBRs was 10%. The variance is the square of the standard deviation.

The results are graphically shown in Figure C.5, where the reliability levels are plotted against traffic for aggregate thicknesses of 6, 8 and 10 inches. From this, it may be determined that the allowable traffic at a reliability level of 50% is approximately twice that at 90%. In short, the reliability factor (F_R) to be used in a design for a 90% level is approximately 2. Figure C.6 summarizes the reliability factors obtained for different thicknesses.

For design, the most conservative factors were selected (i.e. for t=4") and these are the results shown in Section 2.7.

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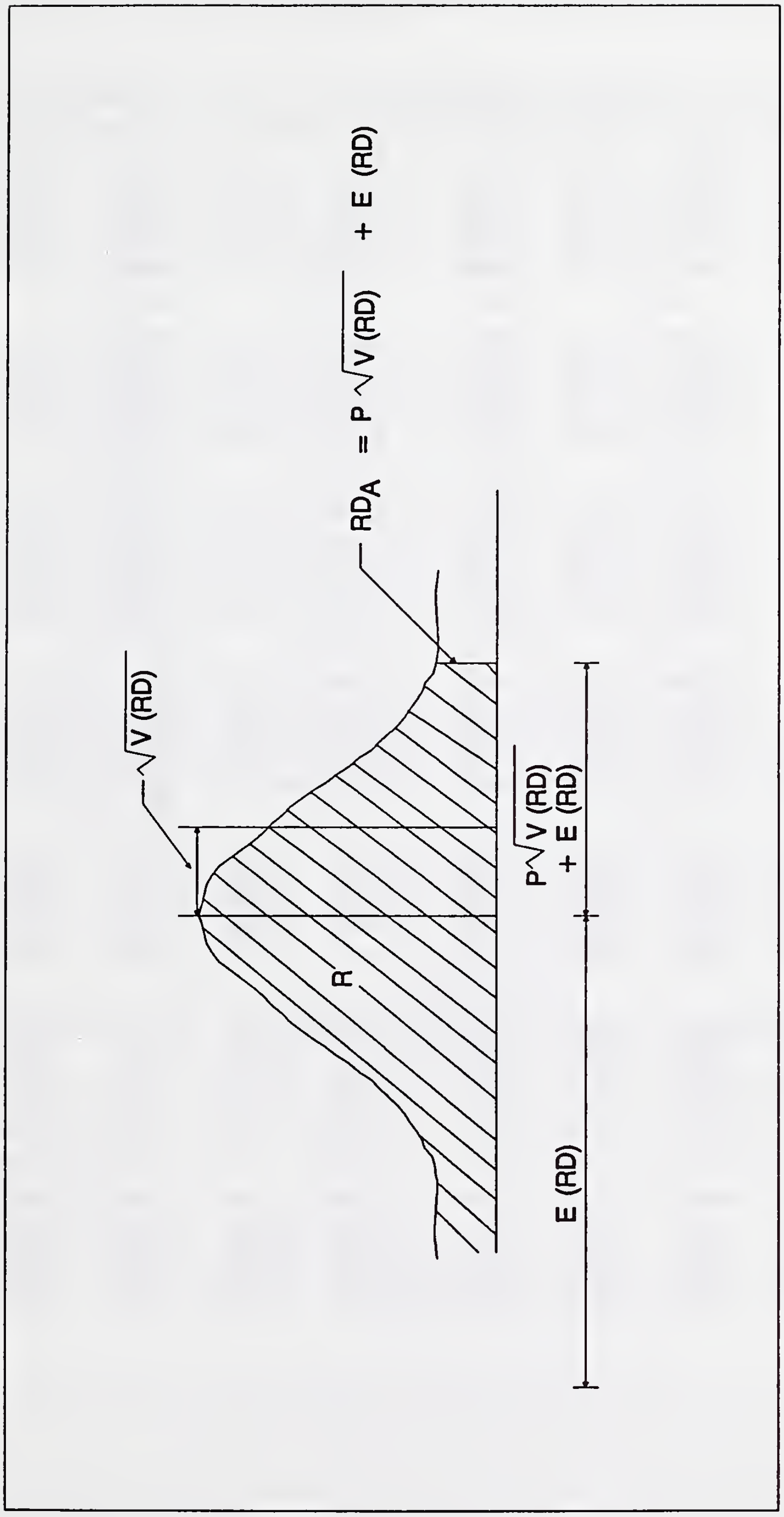

Figure C.2. Standard normal distribution curve illustrating E (RD), $\sqrt{V\ (RD)}$, and RD_A.

Figure C.3 Normal Distribution Function

F(P) = R

P	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.7	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.9	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.0	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.1	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.2	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.3	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.4	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.5	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.6	0.9953	0.9955	0.9956	0.9957	0.9959	0.9960	0.9961	0.9962	0.9963	0.9964
2.7	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.8	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.9	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986
3.0	0.9987	0.9987	0.9987	0.9988	0.9988	0.9989	0.9989	0.9989	0.9990	0.9990
3.0	0.9990	0.9991	0.9991	0.9991	0.9992	0.9992	0.9992	0.9992	0.9993	0.9993
3.2	0.9993	0.9993	0.9994	0.9994	0.9994	0.9994	0.9994	0.9995	0.9995	0.9995
3.3	0.9995	0.9995	0.9995	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9997
3.4	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9998

Figure C.4 Reliability levels for different aggregate thicknesses.

Traffic (ESAL)	Reliability Levels (%)			
	t=4"	t=6"	t=8"	t=10"
8,150	11.24	97.70	99.99	99.99
16,300	2.88	75.36	99.96	99.99
32,600	0.66	33.94	96.06	99.99
65,200	0.15	8.95	66.42	98.32
97,800	0.07	3.45	39.90	89.62
130,400	0.04	1.67	24.26	75.68
163,000	0.02	0.93	15.39	61.18
195,600	0.02	0.58	10.17	48.72
228,200	0.01	0.38	7.02	38.51
260,800	0.01	0.27	5.01	30.57
293,400	0.01	0.19	3.67	24.45
326,000	0.01	0.15	2.77	19.66
489,000	0.01	0.05	0.88	7.55
652,000	0.01	0.02	0.38	3.48
978,000	0.01	0.01	0.11	1.06
1,304,000	0.01	0.01	0.05	0.43
1,630,000	0.01	0.01	0.02	0.21
2,445,000	0.01	0.01	0.01	0.06
3,260,000	0.01	0.01	0.01	0.02

Variables	Mean	Standard Deviation	Variance
Pk(18-kip)	8.64	0.5	0.25 kips
Tire pressure	80	8	64 psi
Agg. CBR, C1	40	4	16 %
Subgrade CBR, C2	10	1	1 %
Allow. Rut Depth	2 inches		

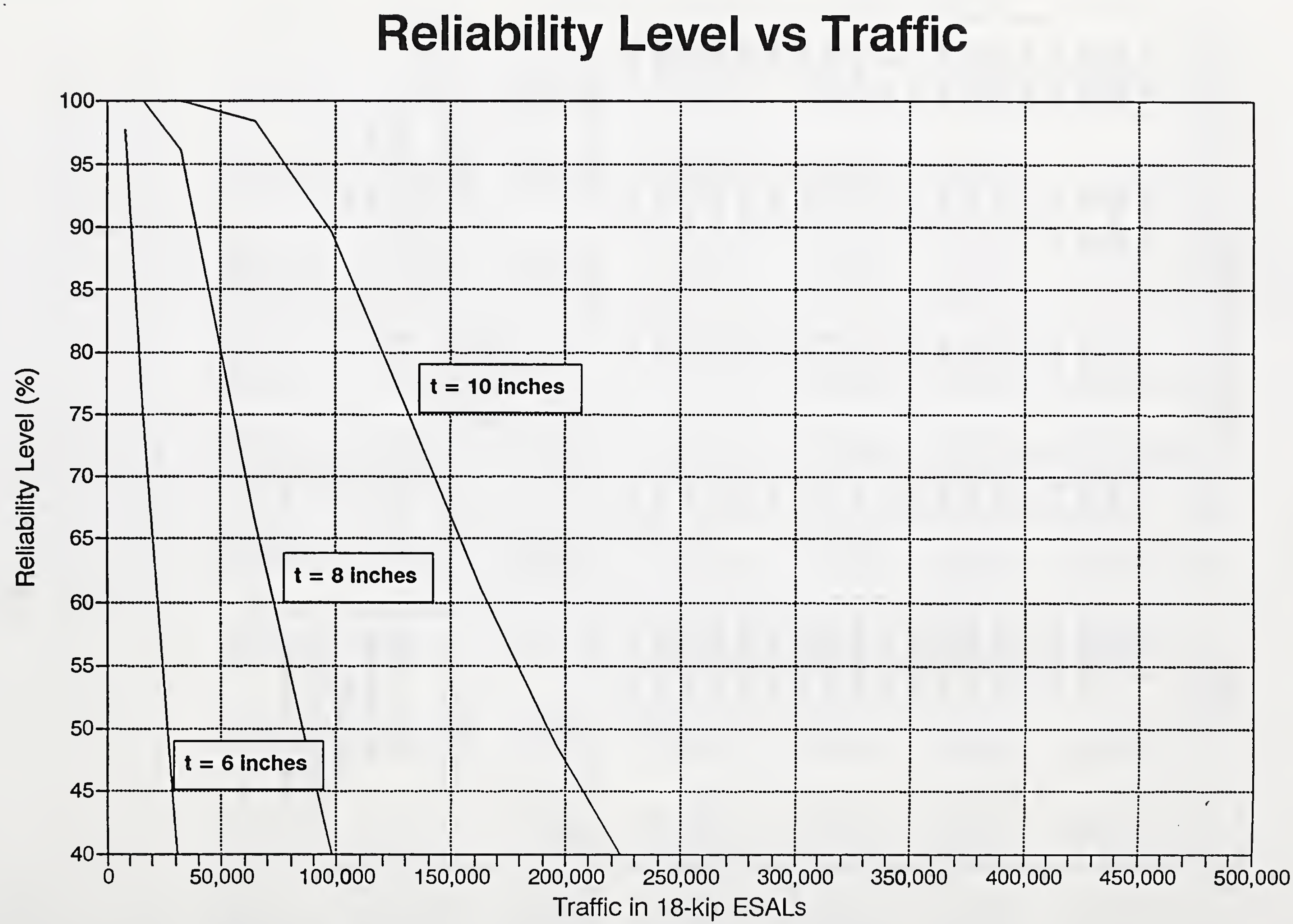

Figure C.5. Reliability level vs traffic

Figure C.6 Reliability Factors for Design

Reliability Level %	F_R for different thicknesses t=4"	t=6"	t=8"	t=10"
50	1.0	1.0	1.0	1.0
70	1.44	1.38	1.36	1.34
90	2.32	2.11	2.03	1.98

APPENDIX D
DESIGN WITH GEOTEXTILES

This appendix is borrowed from Chapter 5, Using Geotextiles as Separators in Roadways in the unpublished report, FHWA Geotextile Design and Construction Guideline by Christopher and Holtz (1989). The Federal Highway Administration (FHWA) is scheduled to publish and distribute the completed report in late 1989 or early 1990.

Editor's notes have been inserted to adapt to Forest Service conditions or explain references not included in the appendix. The USFS Advisory Board has also added Figures 5.2 to 5.16.

Users of this appendix are encouraged to obtain a copy of the referenced FHWA publications on geotextiles for helpful guidance in situations not covered here. These FHWA publications are: FHWA Geotextile Engineering Manual, 1985, FHWA Geotextile Design and Construction Guideline by Christopher and Holtz (1989) and "Guidelines for Use of Fabrics in Construction and Maintenance of Low-Volume Roads," by Steward, Williamson, and Mohney, 1977, Report No. FHWA-TS-78-205.

5.1 Background

A major cause of failure of roadways constructed over soft foundations is contamination of the aggregate base courses with the underlying soft subgrade soils. Contamination occurs both due to:

- o Penetration of the aggregate into the weak subgrade due to localized bearing capacity failure under stresses exerted by the wheel loads, and

- o Intrusion of fine-grained soils into the aggregate because of pumping or subgrade weakening due to excess pore water pressures.

The associated subgrade weakening and loss in aggregate thickness result in inadequate structural support which often leads to premature failure of the system. Subgrade stabilization problems most often occur at sites with fine-grained soils (silts and clays) with a high water content, some sensitivity to remolding, and low undrained shear strength. If the ground water table is also at or near the surface, problems during construction can occur.

A geotextile can be placed between the aggregate and the subgrade to act as a <u>separator</u> to prevent the subgrade and aggregate base course from mixing and, thus, maintain the desired design thickness of the roadway. As such, the primary function of the geotextile in roadway applications is separation. The system may also be influenced by secondary functions of the geotextile including filtration, drainage, and reinforcement. The geotextile acts as a filter to prevent fines from migrating into the aggregate due to high water pressures and as a drain by allowing pore water dissipation in the underlying soil through the geotextile. In addition, the geotextile may provide reinforcement through:

1. <u>Lateral restraint of the base and subgrade</u> through friction between the aggregate, soil and the geotextile,

2. <u>Increase in the bearing capacity of the system</u> by interfering with the incipient bearing capacity failure surface, which forces the failure surface along an alternate surface.

3. <u>A membrane support</u> of the wheel loads.

These mechanisms are also applicable to geogrids when they are used in roadways. However, grids are not able to provide the separation and filtration functions, and therefore they must be used together with a geotextile in roadway applications.

The primary and secondary functions of geotextiles in roadway applications are shown in Figure 5.1.

These geotextile functions, when considered in the design of roadways over soft subgrades, can lead to several possible cost and performance benefits including:

1. Reducing the intensity of stress on the subgrade and preventing the subbase aggregate from penetrating into the subgrade (function: separation).

2. Preventing subgrade fines from pumping into the subbase (function: separation and filtration).

3. Preventing contamination of the subbase materials which may allow more open-graded free draining aggregate to be considered in the design (function: filtration).

4. Reducing the depth of excavation required for removal of unsuitable subgrade materials (function: separation and reinforcement).

5. Reducing aggregate thickness required to stabilize the subgrade (function: separation and reinforcement). (Aggregate reduction in the structural design may or may not be considered.)

6. Providing for less subgrade disturbance during construction (function: separation and reinforcement).

7. Maintaining the integrity and uniformity of the pavement should settlement of the subgrade occur (function: reinforcement). The geotextile does not prevent settlement of the subgrade, but its use can result in more uniform settlement (Boutrup and Holtz, 1983). Geotextiles will also aid in reducing differential settlement in transition areas from cut to fill.

8. Reducing maintenance and extending the life of the pavement (functions: all).

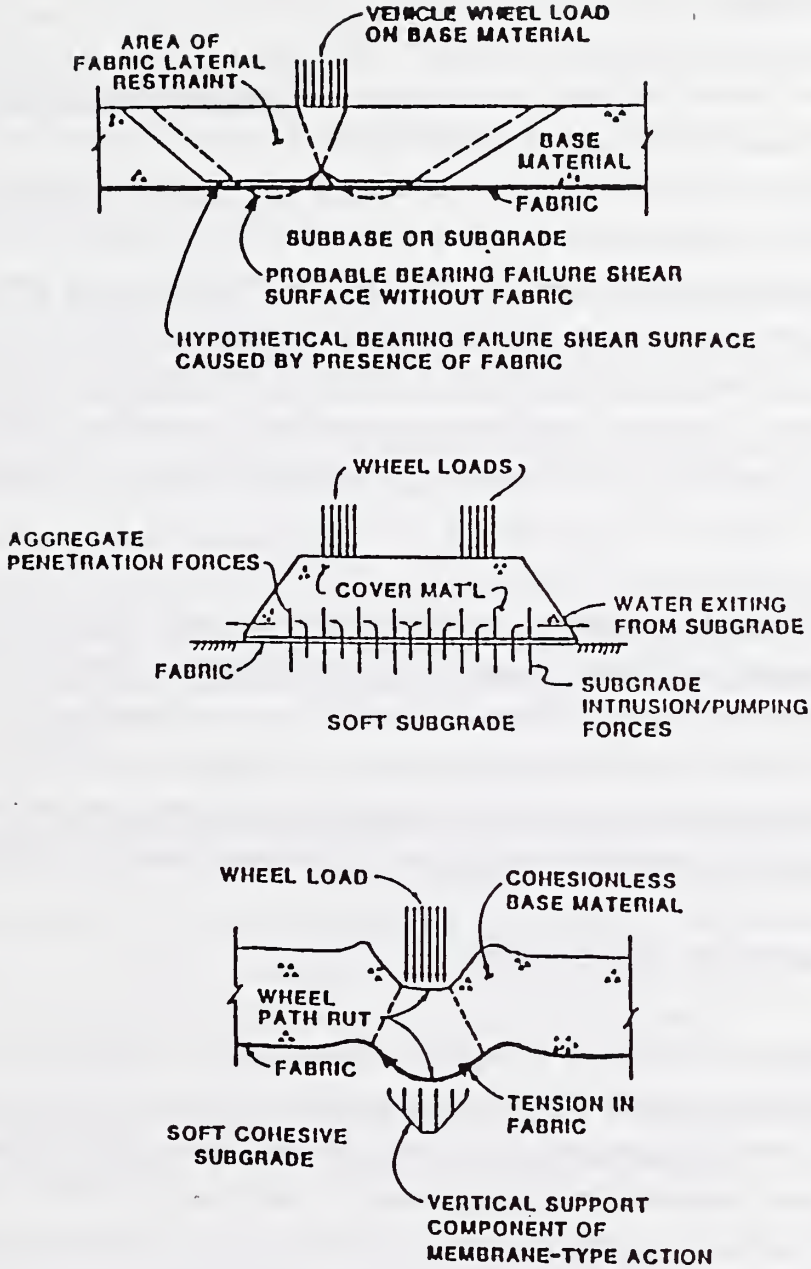

Figure 5.1. Primary and Secondary Functions of Geotextile in Roadway Applications

The following sections will discuss geotextile selection and design methodology to take advantage of the above possible benefits.

5.2 Applications

On the basis of service life, traffic, or desired performance roads are broadly classified into two categories, permanent and temporary. Permanent roads include both paved and unpaved systems which are required to remain in service over a number of years, usually 10 or more. Permanent roads may be required to handle well over one million vehicles during the design life of the road (typically more on the order of 1×10^9 vehicles). On the other hand, temporary roads, such as haul roads and access roads are, in most cases, unpaved, required to remain in service for short periods of time (usually less than one year) and are usually required to support less than 10,000 vehicles during the life of the system. Temporary roads also include detours, construction platforms, and stabilized working tables required for the construction of permanent roads and embankments over soft subgrades.

One of the most significant geotextile applications is allowing access of construction equipment into sites where the soils are too weak to support the initial construction efforts. It is often the case that even if the finished road section could be supported by the subgrade, there may be no way of actually placing the construction excavation and replacement with select granular materials. Such sites require stabilization through demucking, placement of stabilization aggregate, lime stabilization or other similar expensive operations. Geotextiles can often be a cost-effective alternate to these procedures.

5.3 Roadway Design Using Geotextiles

Certain principles are common to all types of roadway systems, regardless of the design method. Basically, the design of any roadway involves a study of each of the components of the system, including the pavement, aggregate base courses and subgrade, as to their behavior under load and their ability when placed in the roadway section to carry that load under various climatic and environmental conditions. All roadway systems, whether permanent or temporary, derive their support from the underlying subgrade[1]. Thus, the geotextile functions are similar for either temporary or

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[1]Ed. Note: "Temporary Roads" are comparable to aggregate-surfaced local and collector roads accessing areas for timber harvest and rock haul. These types of roads are designed to develop visible and measurable rutting in the surface during their design life. "Permanent Roads" are comparable to higher volume, aggregate-surfaced, arterial roads and asphalt-surfaced roads. For these low-rutting roads using geotextiles, please see the parent documents, FHWA Geotextile Engineering Manual, 1985 and FHWA Geotextile Design

permanent roadway applications. However, due to roadway performance requirements, design methodologies for temporary roads cannot be used to design permanent roads. The main difference in the design is related to the performance requirements. Temporary roadway design usually allows for some rutting to occur over the design life as rutting may not necessarily impair service. Obviously, ruts are not desirable in permanent roadways. Therefore, the design of geotextiles in these two applications will be presented separately.

5.4 Design Guidelines for Temporary Roads

There are two main approaches to design of unpaved roads. The first approach assumes no reinforcing effect of the geotextile; that is, the geotextile acts as a separator only. The second approach does take a possible reinforcing effect of the geotextile into consideration. It appears that the separation function is more important for low embankments with relatively small live loads where ruts, on the order of 2 to 4 inches, are anticipated. In these cases, a design which assumes no reinforcing effect is generally conservative. On the other hand, for large live loads on thin embankments where deep ruts (>4 inches) may occur and for higher embankments on softer subgrades, the reinforcing function becomes increasingly more important if stability is to be maintained. It is for these latter cases that analyses considering reinforcing have been developed and appear to be appropriate.

The method presented in these guidelines considers mainly the separation function. It was selected because it can be adapted to a wide variety of conditions. Other design methods considering reinforcing are covered in the FHWA Geotextile Engineering Manual. For roadway embankments where stability of the foundation is questionable, you should refer to Chapter 5 in the Manual[2] and Chapter 7 in these guidelines[3] for information on reinforced embankments.

The design method presented herein was developed by Steward, Williamson and Mohney (1977) for the U.S. Forest Service (USFS). The method allows the designer to consider:

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and Construction Guidelines, by Christopher & Holtz (1989).

[2]Ed Note: "Manual" refers to the FHWA Geotextile Engineering Manual used for implementation workshops in 1985-1987.

[3]Ed Note: "Guidelines" refers to the FHWA Geotextile Design and Construction Guideline by Christopher and Holtz (1989).

- o Number of vehicle passes (up to 10,000)
- o Equivalent axle loads
- o Axle configurations
- o Tire pressures
- o Subgrade strengths
- o Rut depths

The following limitations apply:

- o The aggregate layer must be:
  - a) Compacted to CBR 80[4]
  - b) Cohesionless (non-plastic)
- o Vehicle passes are limited to 10,000
- o Geotextile survivability criteria must be considered
- o Subgrade shear strength as measured by the CBR, less than 3

For subgrades stronger than CBR of 3, geotextiles are rarely required for separation, although they may provide for some drainage and filtration. In this case, the principles developed in Chapter 2 are applicable, just as they are for weaker subgrades.

The design method is based on both theoretical analysis and empirical (laboratory and field) tests. Based on these results, Steward, et al. (1977) determined that a certain amount of rutting would occur under different traffic conditions, both with and without a geotextile separator, for a given stress level acting on the subgrade. They present this stress level in terms of a classical bearing capacity factor. These factors and conditions are given in Table 5-1.

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[4]Ed Note: Compaction is typically performed by hauling vehicles and tracked vehicles used for spreading the aggregate. Aggregates having compacted CBR less than 80 may be used over the geotextile; however, CBR 80 material is required to support repeated wheel loads.

TABLE 5-1

BEARING CAPACITY FACTORS FOR DIFFERENT RUTS AND TRAFFIC CONDITIONS BOTH WITH AND WITHOUT GEOTEXTILE SEPARATORS

(After Steward, Williamson, and Mohney, 1977)

	Ruts (in.)	(Passes of 18 kip axle equivs.)	Bearing Capacity Factor, N_c
Without Geotextile:	<2	>1000	2.8
	>4	<100	3.3
With Geotextile:	<2	>1000	5.0
	>4	<100	6.0

The following design procedure is recommended:

1. Determine the subgrade soils strength in the field using the field CBR test, cone penetrometer, or vane shear test. The undrained shear strength of the soil, c, can be obtained from the following relationships:[5]

   o For field CBR, c in psi = 4 X CBR.
   o For the WES cone penetrometer, c = cone index divided by 10 or 11.
   o For the vane shear test, c is directly measured.

   Other in-situ tests such as the Dutch cone penetrometer test (CPT) may be used, provided local correlations with undrained shear strength exist. Use of the Standard Penetration Test (SPT) is not recommended for soft clays.

2. Make the strength determinations at several locations where the soil appears to be the weakest. Strength should be evaluated at a depth of 0 to 9 inches and from 9 to 18 inches; 6 to 10 strength measurements recommended at each location to obtain a

[5]Ed Note: The strength relationships used are general and approximate. Carefully read the manufacturers literature for shear vanes and cone penetrometers to determine the soil strength parameter being measured. Calibrate the field test equipment when in doubt.

good average value.[6]

3. Determine the maximum single wheel load, tire pressure, maximum dual wheel load, tire pressure and the maximum dual tandem wheel load and tire pressure anticipated for the road during the design period. For example, a 10 yd^3 dump truck with tandem axles will have a dual wheel load of approximately 8,000 lb. A motor grader has a wheel load of approximately 5,000 to 10,000 lb.

4. Estimate the maximum amount of traffic anticipated for each design vehicle class.

5. Establish the amount of tolerable rutting during the design life of the roadway. For example, 2 to 3 inches of rutting is generally acceptable during construction.

6. Obtain appropriate subgrade stress level in terms of the bearing capacity factors in Table 5-1.

7. Determine the required aggregate thickness from the USFS design (Figures 5.2 to 5.16) for each maximum loading. Enter the curve with bearing capacity factors (N_c) of 2.8, 3.3, 5.0 and 6.0 times the design[7] subgrade undrained shear strength (c) to evaluate each required stress level ($C \cdot N_c$).

8. Select the design thickness based on the design requirements. The design depth should be given to the next highest 1 inch thickness as obtained from Step 5.

9. Check the geotextile drainage and filtration requirements gradation of the subgrade, the permeability of the subgrade, the water table conditions, and the retention and permeability criteria given in Chapter 2. In high water table conditions, filtration criteria may also be required.

10. Check the survivability criteria as discussed in Section 5.7.

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[6]Ed Note: Take enough tests at each location (say within a 3 foot diameter area) and depth to determine the range of readings for each area.

[7]Ed Note: The design subgrade shear strength is recommended at the 75th percentile (75% of measurements higher than design value).

Figure 5.2 Single Wheel Load, One Layer System, Tire Pressure = 25 psi

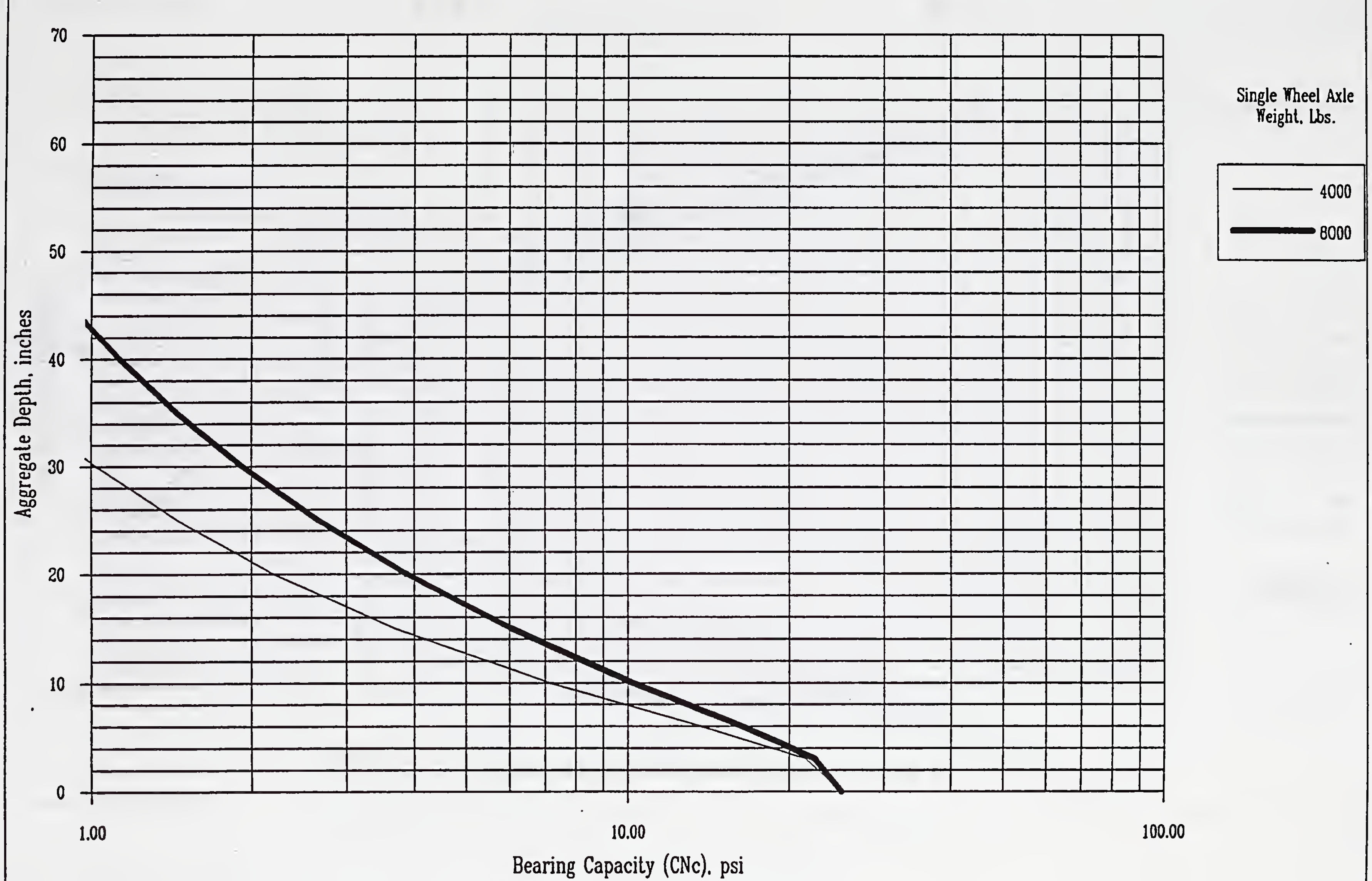


Figure 5.3 Single Wheel Load, One Layer System, Tire Pressure = 45 psi

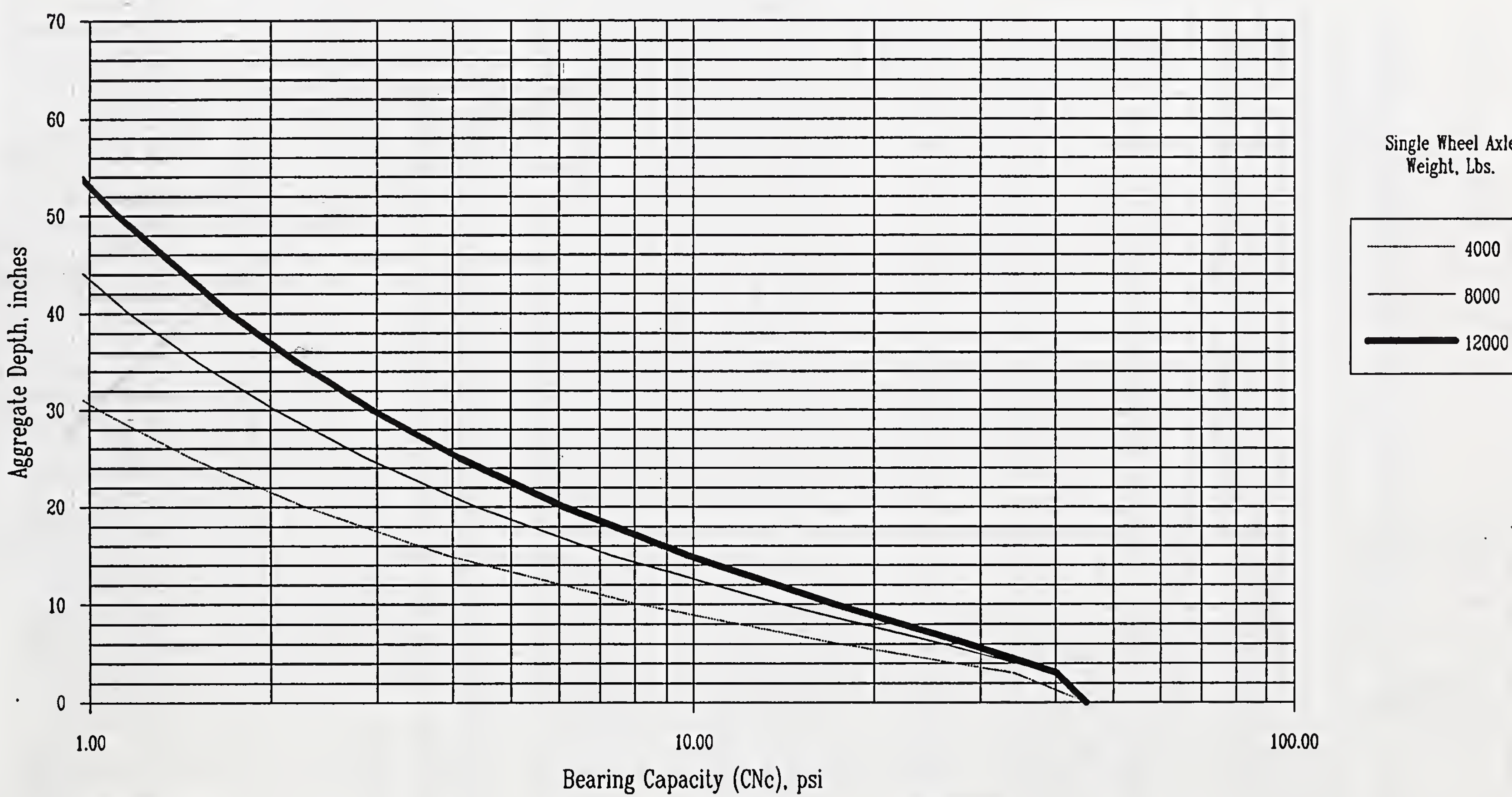


Figure 5.4 Single Wheel Load, One Layer System, Tire Pressure = 70 psi

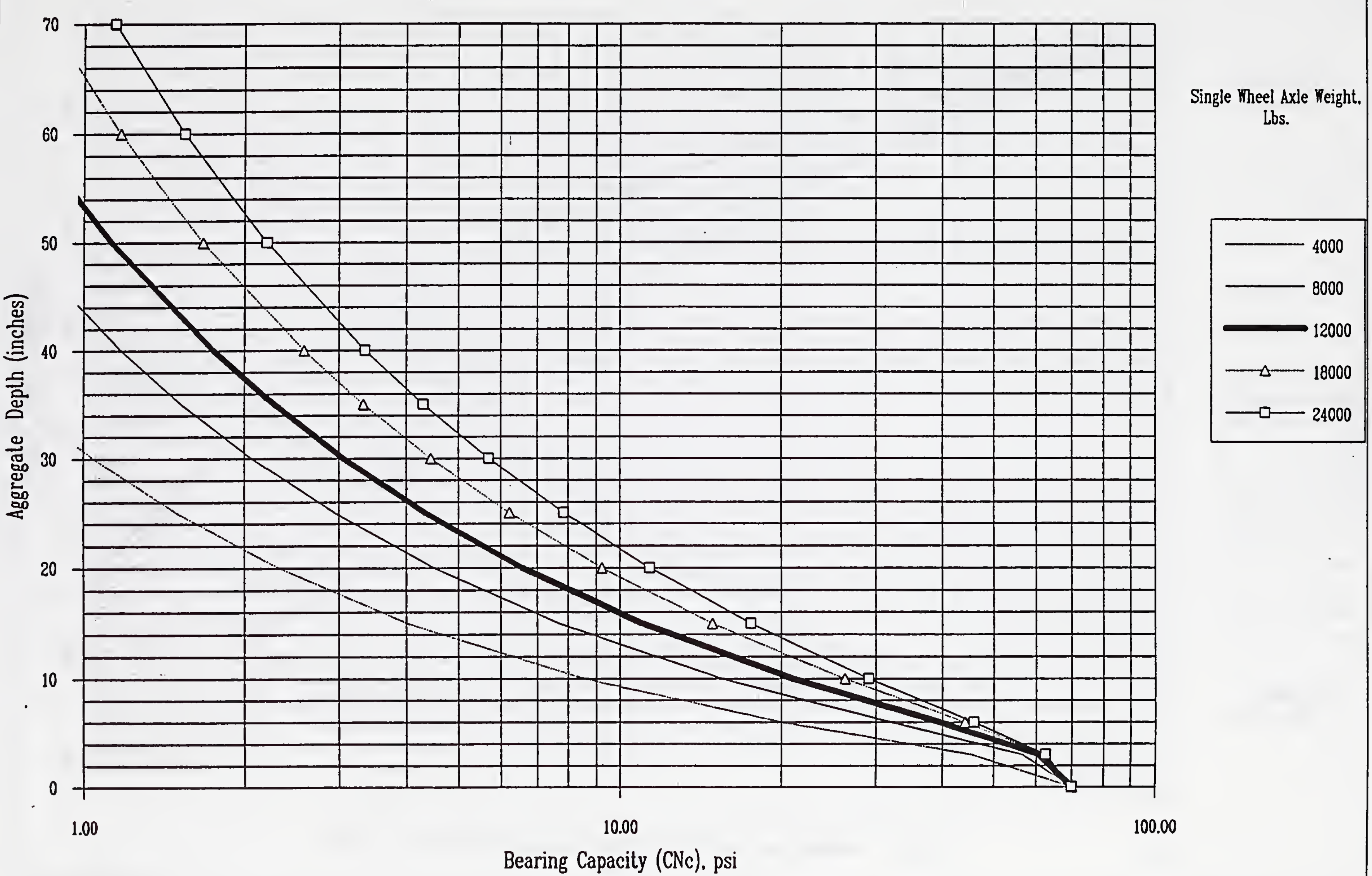


Figure 5.5 Single Wheel Load, One Layer System, Tire Pressure = 90 psi

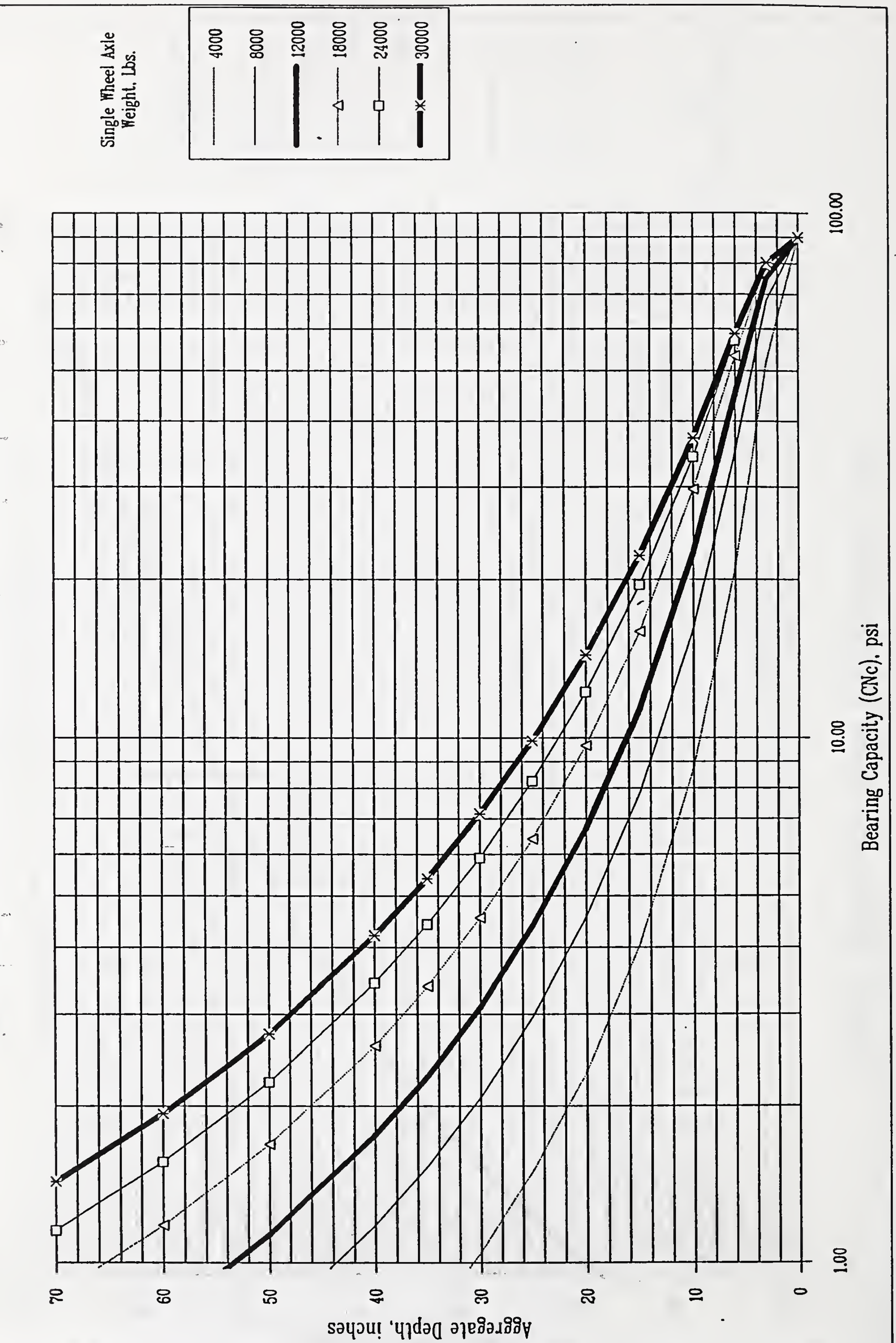


Figure 5.6 Single Wheel Load, One Layer System, Tire Pressure = 110 psi

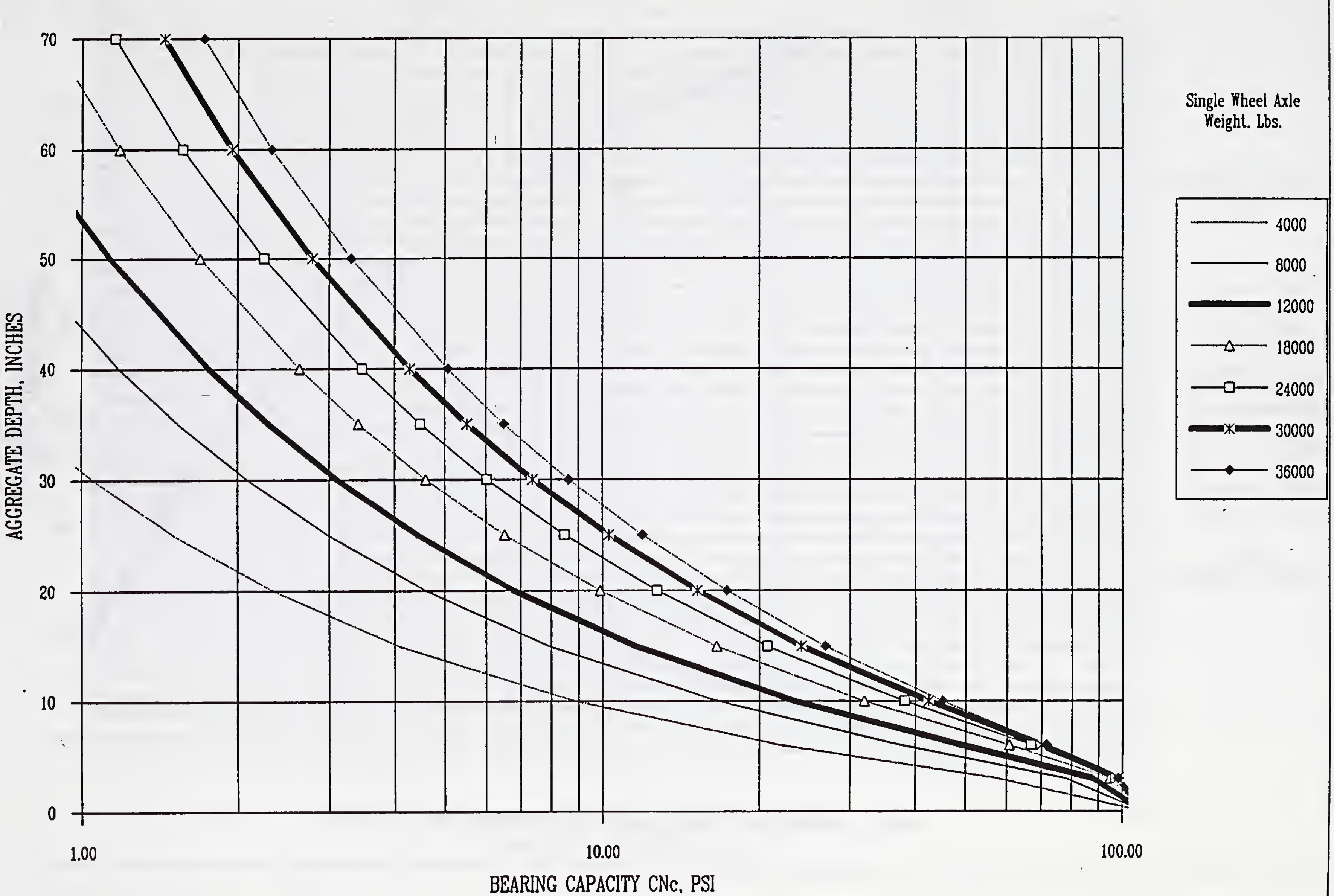
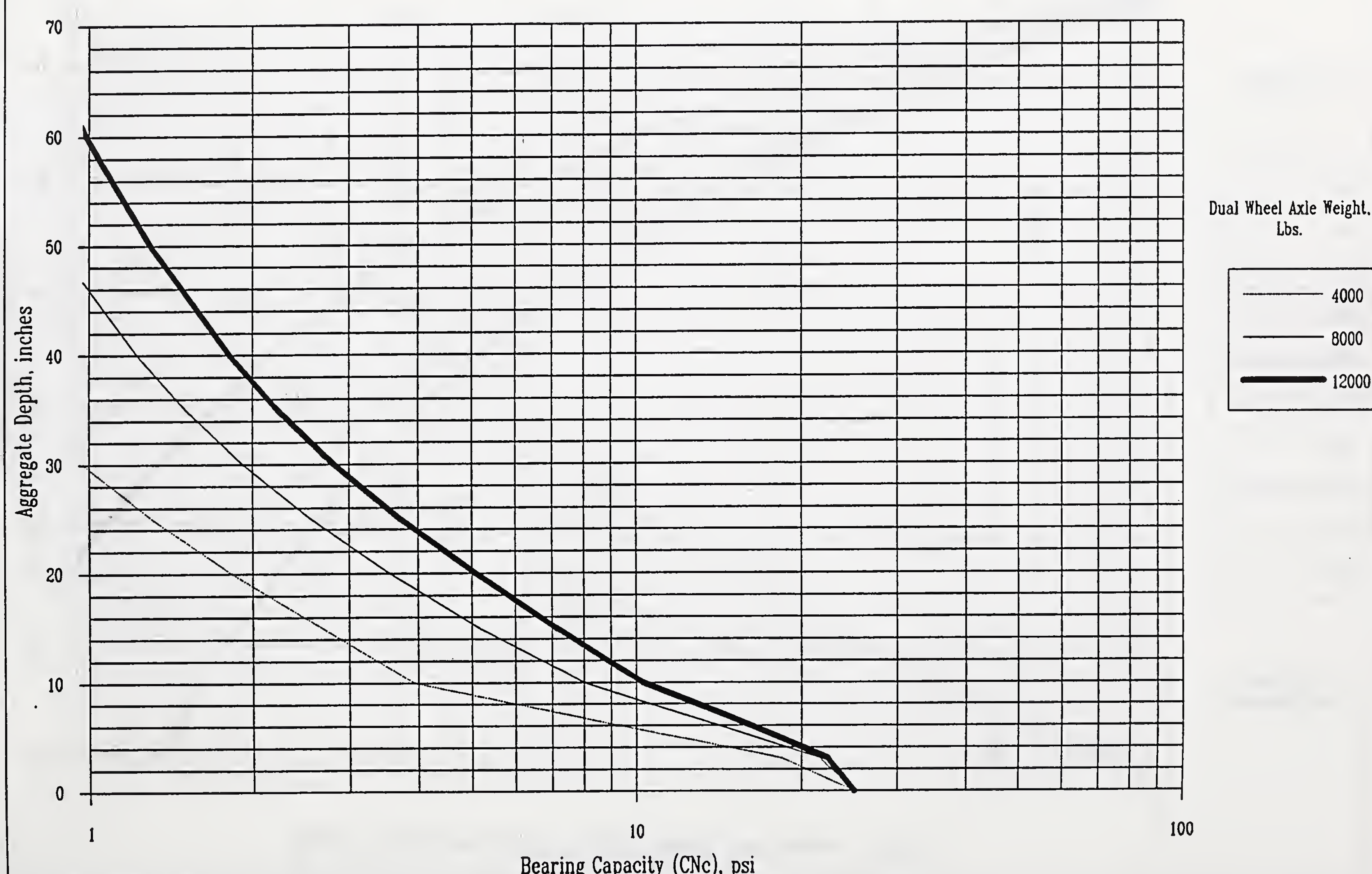


Figure 5.7 Dual Wheel Load, One Layer System, Tire Pressure = 25 psi



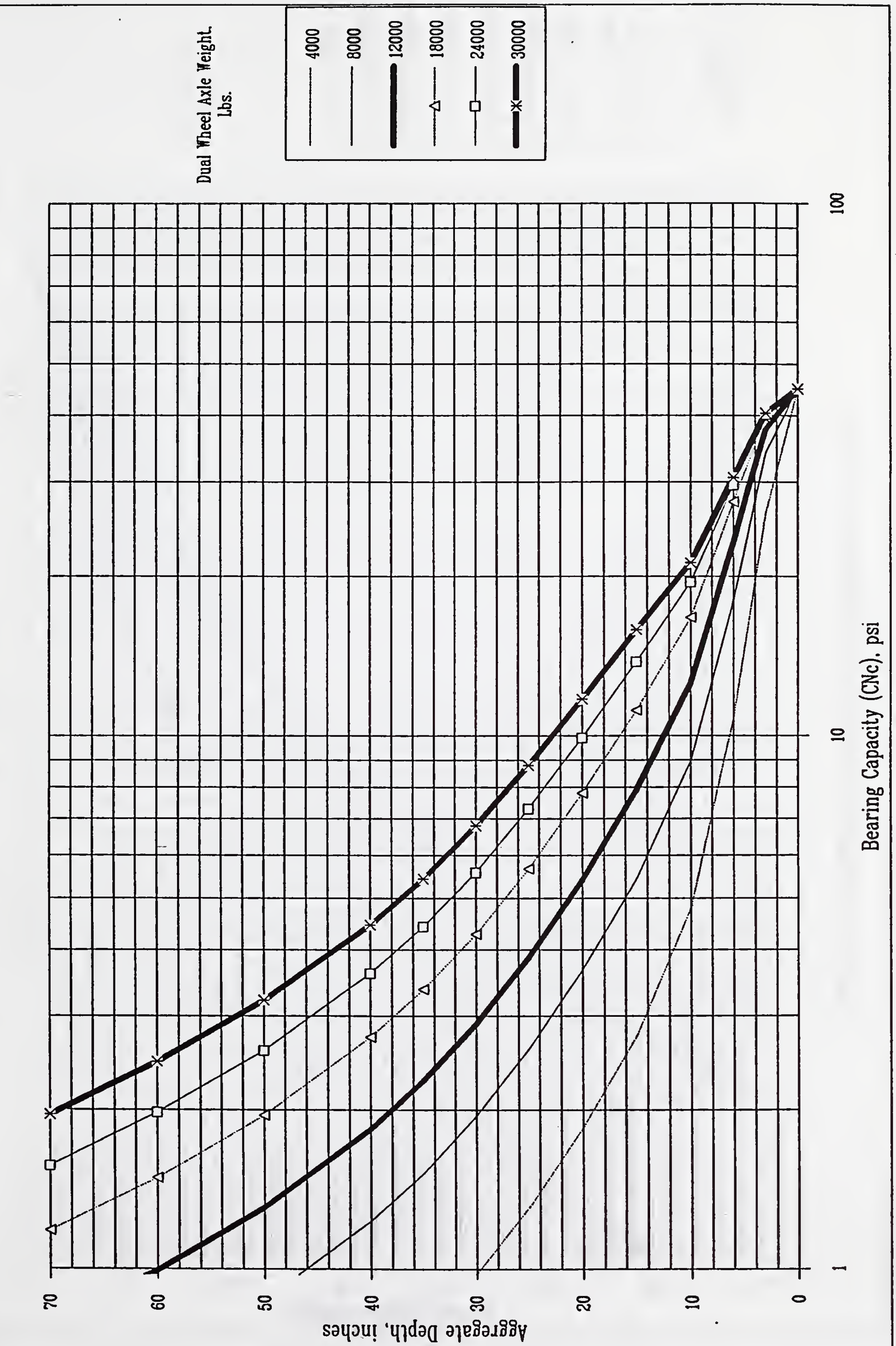


Figure 5.8 Dual Wheel Load, One Layer System, Tire Pressure = 45 psi

Figure 5.9 Dual Wheel Load, One Layer System, Tire Pressure = 70 psi

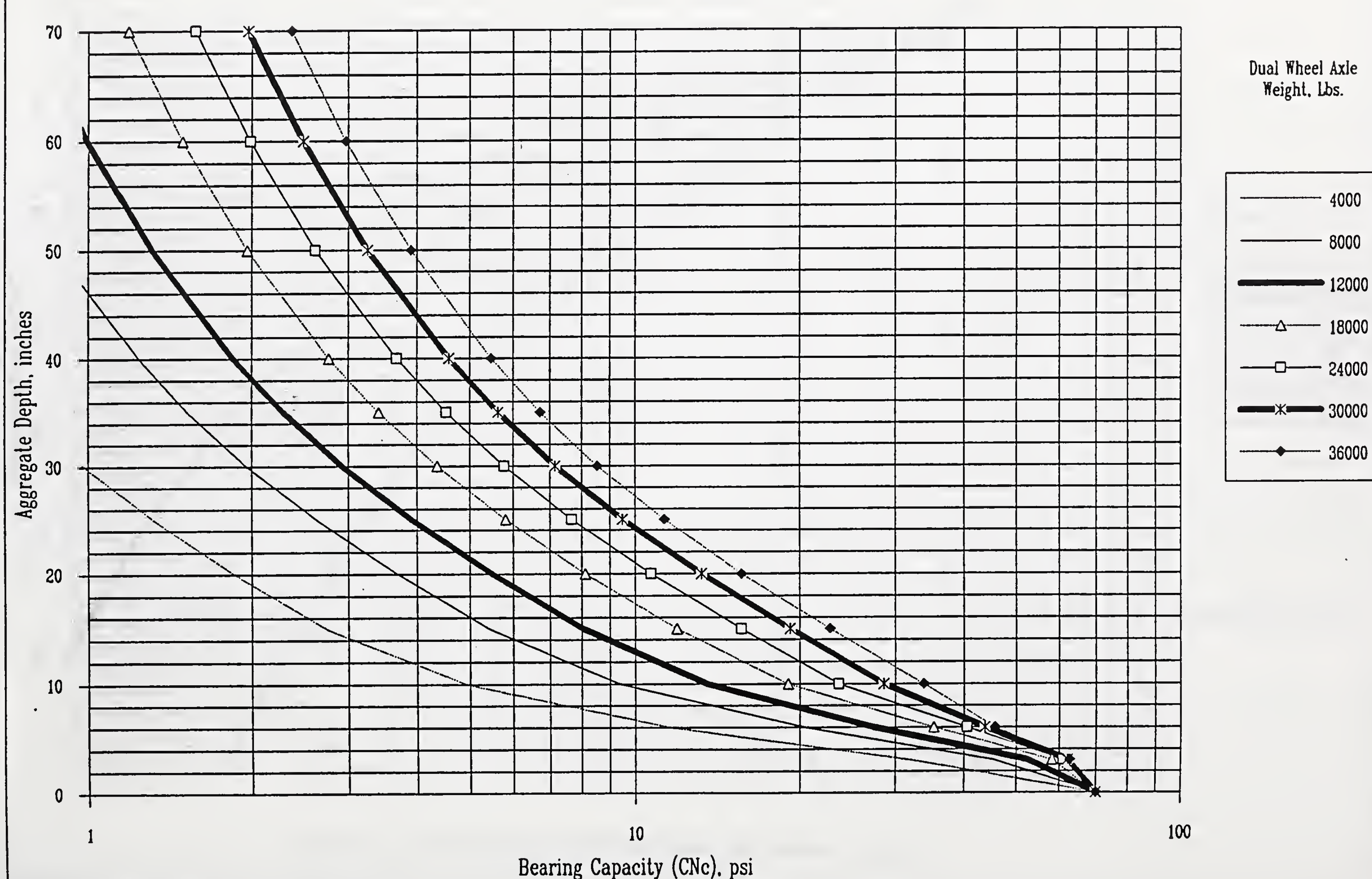


Figure 5.10 Dual Wheel Load, One Layer System, Tire Pressure = 90 psi

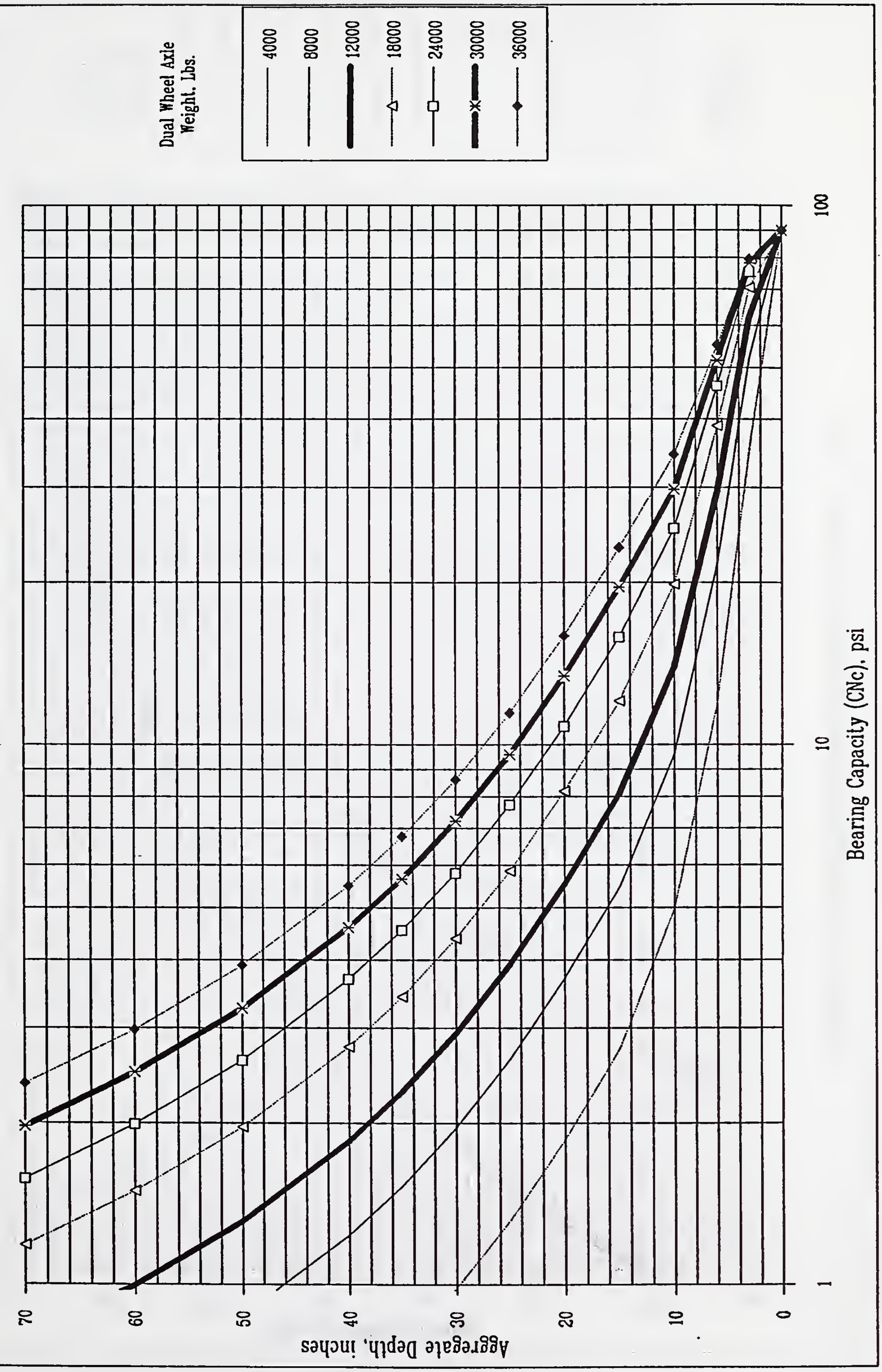


Figure 5.11 Dual Wheel Load, One Layer System, Tire Pressure = 110 psi

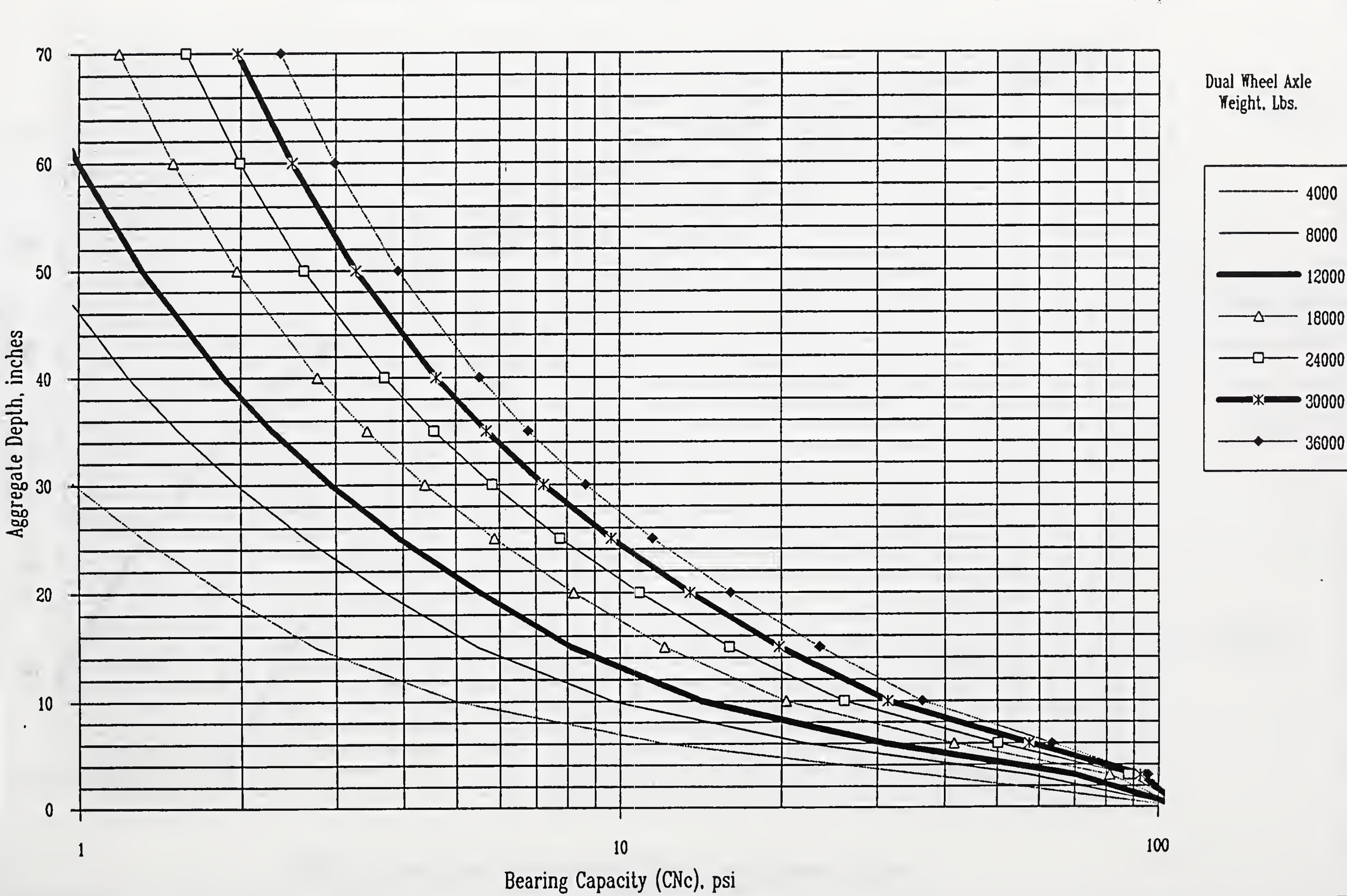


Figure 5.12 Tandem Axle Load, One Layer System, Tire Pressure = 25 psi

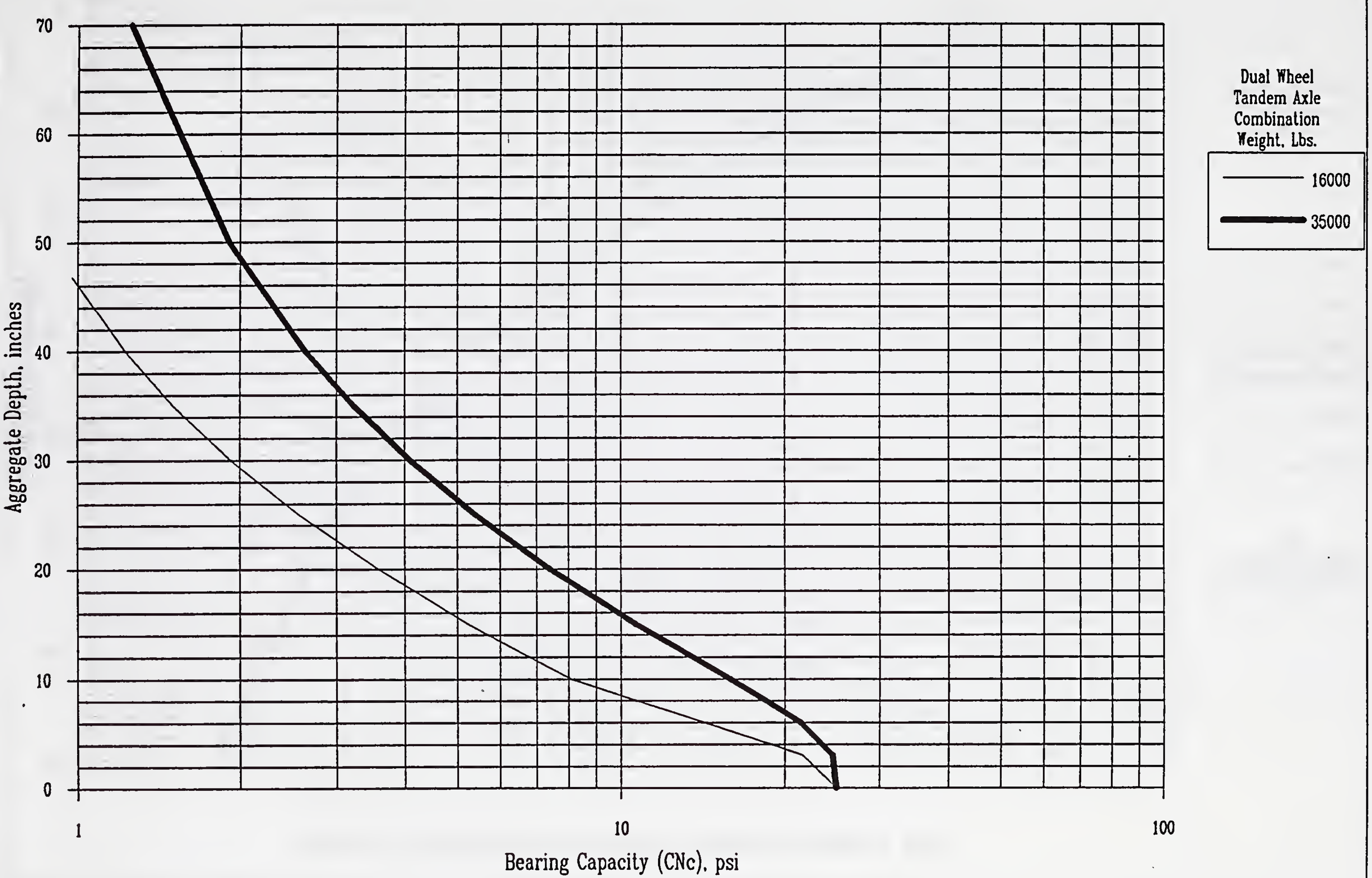


Figure 5.13 Tandem Axle Load, One Layer System, Tire Pressure = 45 psi

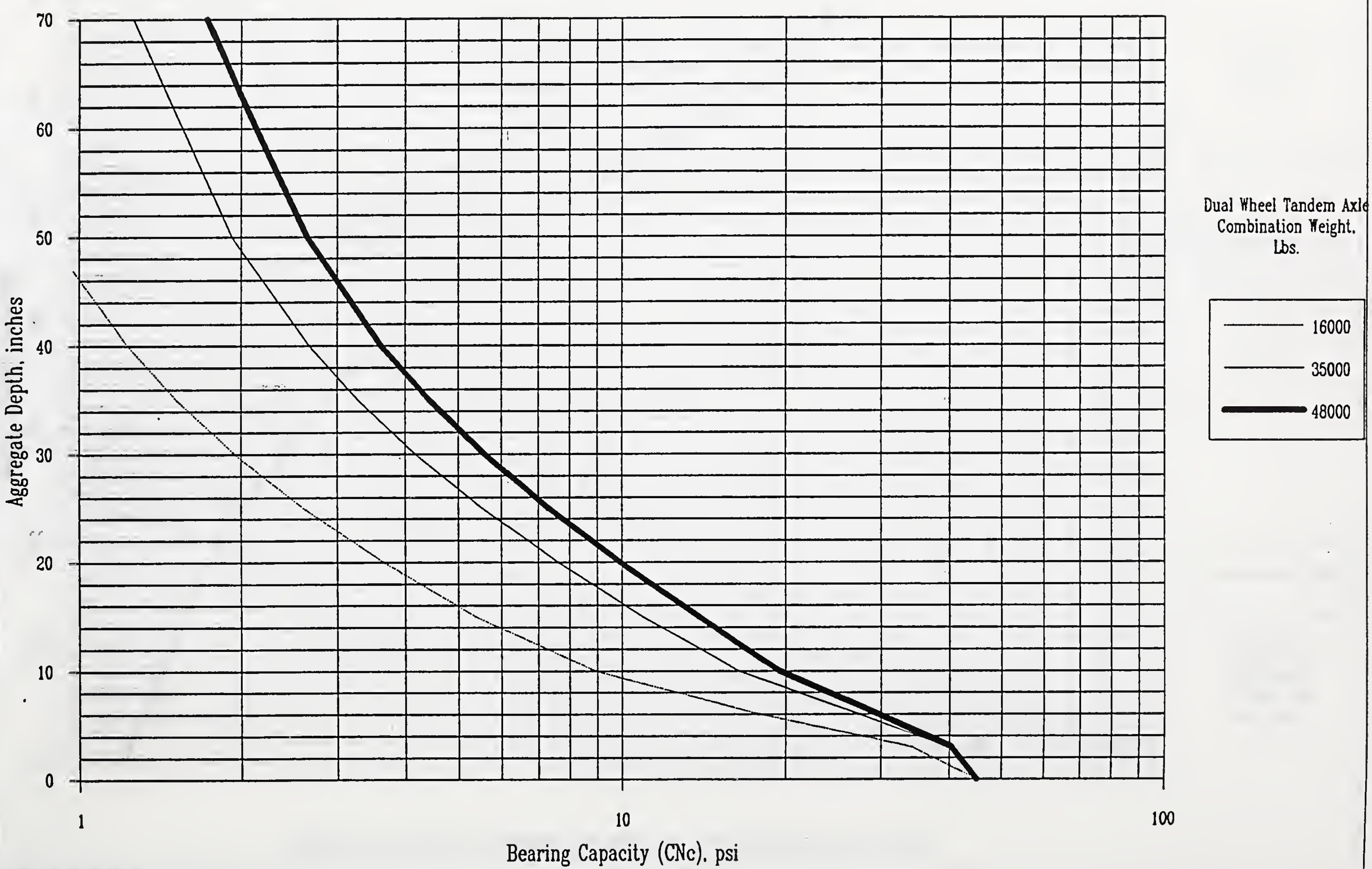


Figure 5.14 Tandem Axle Load, One Layer System, Tire Pressure = 70 psi

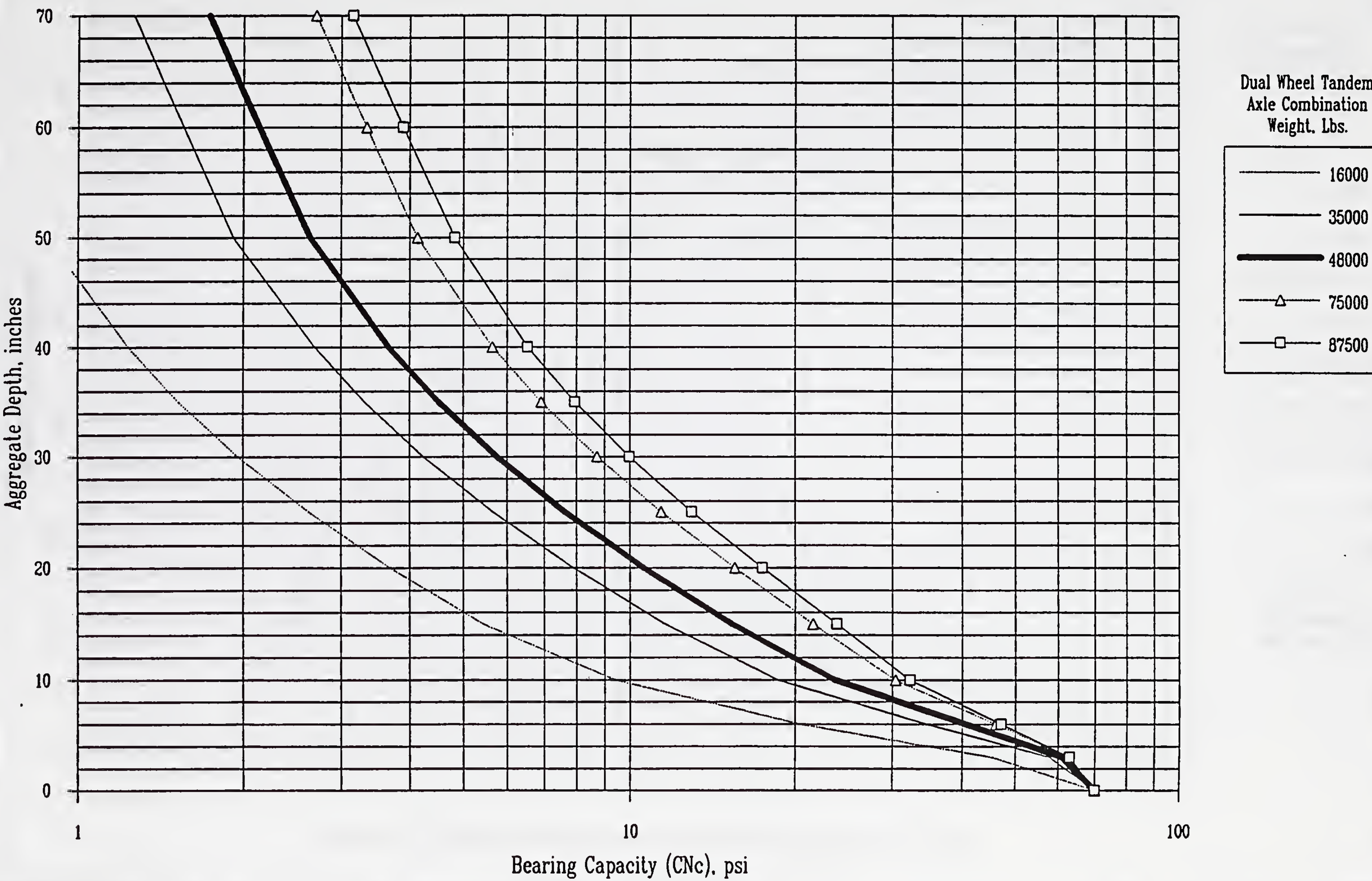


Figure 5.15 Tandem Axle Load, One Layer System, Tire Pressure = 90 psi

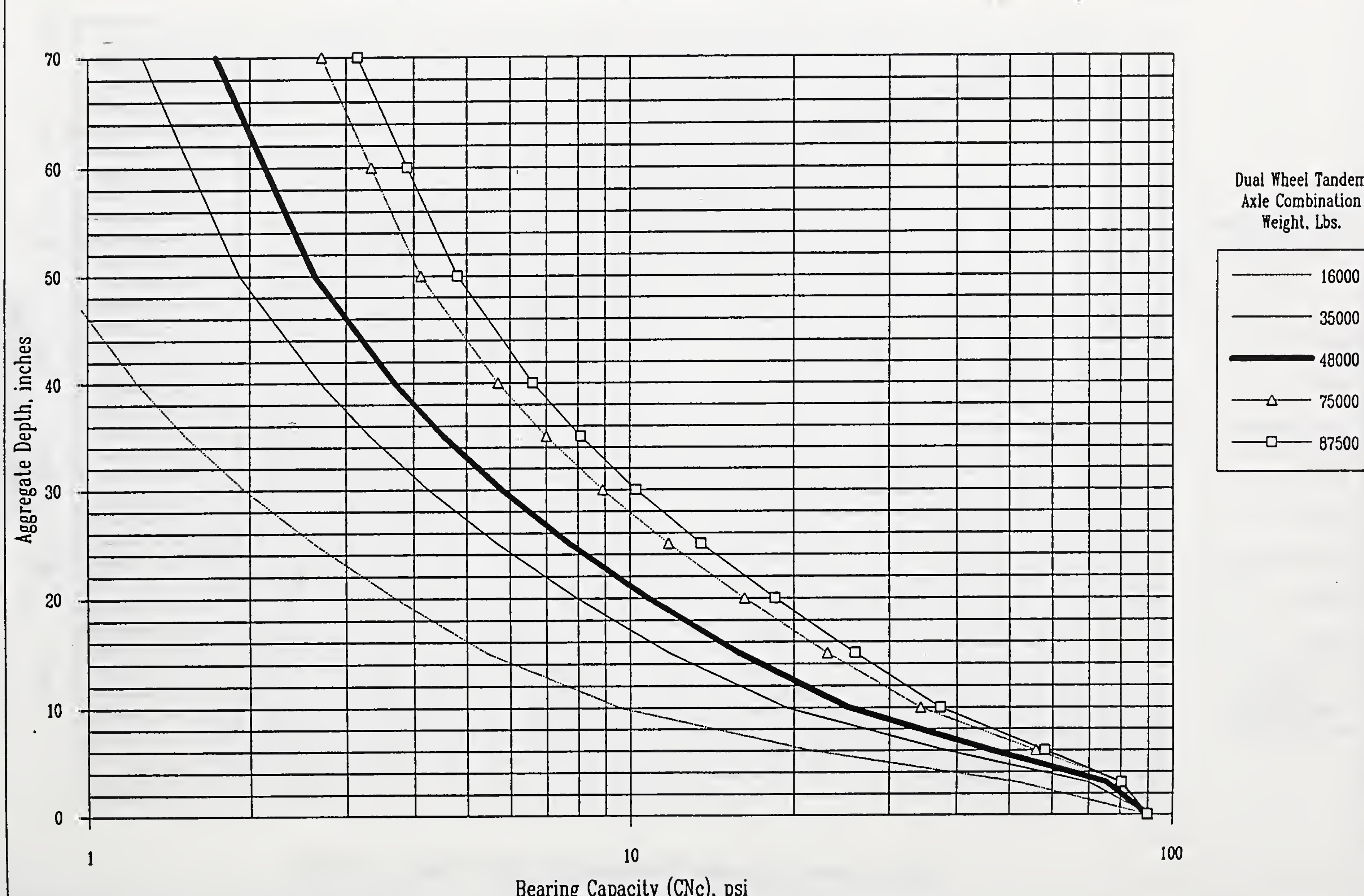
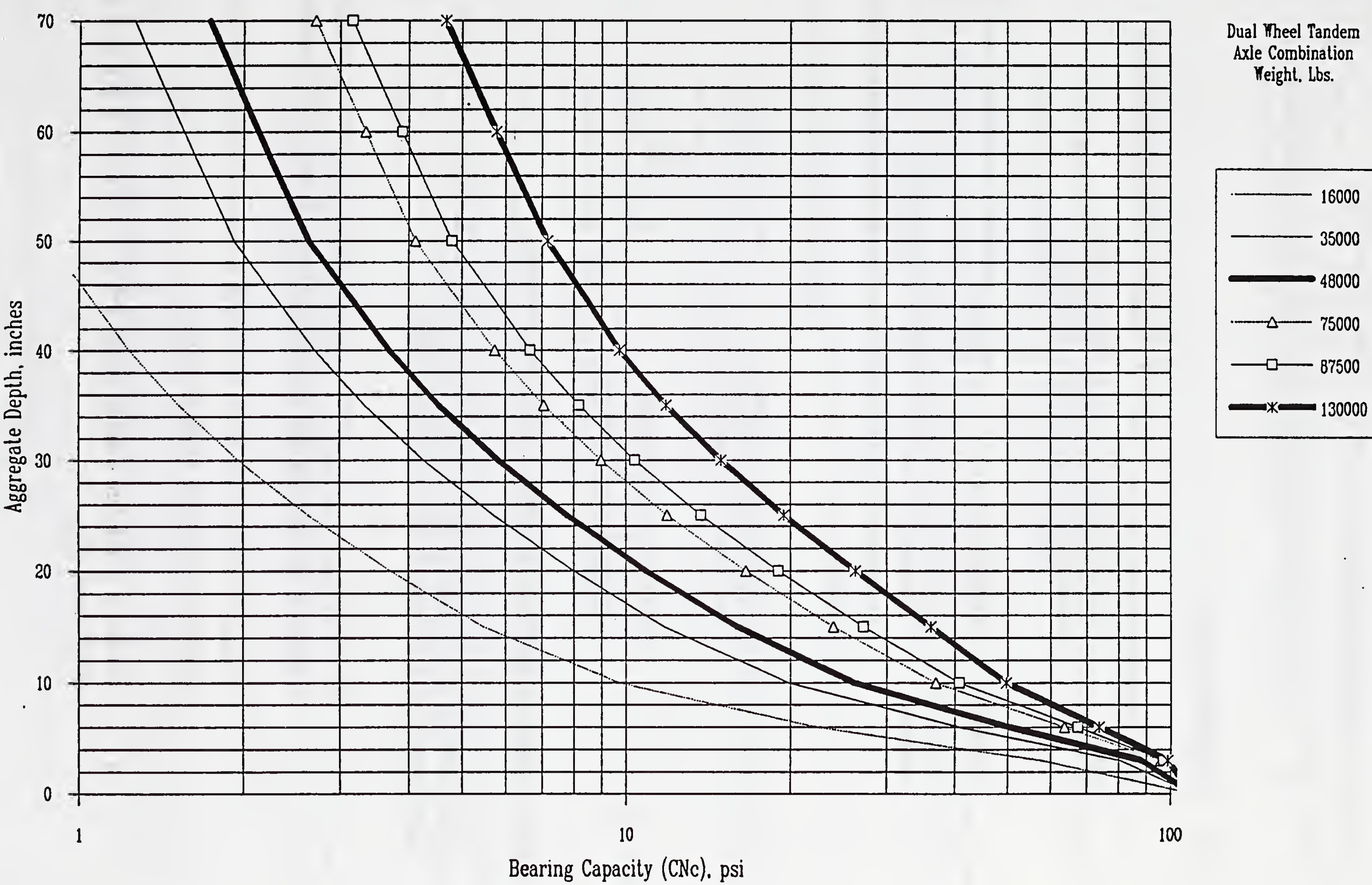


Figure 5.16 Tandem Axle Load, One Layer System, Tire Pressure = 110 psi



11. Specify geotextiles which meet or exceed these criteria.

12. Follow construction recommendations as covered in Section 5.11.

5.5 Geotextile Example

Strength measurements (field c values): 7.5, 6.9, 4.9, 4.2, 3.7, 3.0, 3.0, 2.5, 2.4

Given: 1000 passes of log truck @ 80,000 GVW
(dual wheel tandem weight = 35,000 lbs)

Determine: Aggregate depth with and without geotextile if tire pressure was 70 psi

Solution: Determine 75th percentile strength measurement
(strength value at which 75% of the soil strength readings are higher than this value) = 3.0

For 70 psi without geotextile $cN_c = 3(2.8) = 8.4$
from Figure 5.14, depth = 19"

For 70 psi with geotextile $cN_c = 3(5.0) = 15$
from Figure 5.14, depth =11"

5.6 Design Guidelines For Permanent Roads and Highways

The recommended design methods for permanent roads, as discussed in the FHWA Geotextile Engineering Manual, is based on the following concepts:

1. No structural support is assumed to be provided by the geotextile and therefore no reduction is allowed in aggregate thickness required for structural support.

2. Aggregate savings will be achieved through a reduction in the required stabilization aggregate not used for structural support.

3. Standard methods are used to design the overall pavement system (i.e. AASHTO, CBR, R-value, etc.).

4. The design method is actually used to design the first lift, which is called the "stabilizer lift" since it provides sufficient stabilization to the subgrade to allow access of normal construction equipment for the remaining lifts.

5. Once the stabilizer lift is complete, the construction can proceed normally as per standard road design methods.

6. The method does not include evaluation of settlement or drainage requirements, which must also be considered as in a conventional design.

Basically, the method assumes that the stabilizer lift is actually an unpaved road which will be exposed to relatively few vehicle passes (i.e., construction equipment only) and which can tolerate 2 to 3 inches of rutting under the equipment loads.

The design consists of the following steps:

1. Estimate the need for a geotextile based on the subgrade strength (CBR<3) and by past performance in similar types of soils.

2. Design the roadway for structural support using your normal permanent pavement design methods; provide no allowance for the geotextile.

3. Determine if additional subbase[8] over that required for structural support has been added due to susceptibility of soils to pumping and subbase intrusion. If so, reduce that subbase by 50% and include a geotextile in the design at the subbase/subgrade interface.

4. Determine additional subbase required for stabilization of subgrade during construction activities using a 3 inch rutting criteria for construction equipment and the procedures outlined in Section 5.4, Design Guidelines for Temporary Roads.

5. Compare the subbase geotextile system determined for constructability in Step 4 with the geotextile subbase system determined in Step 3 and use the system with the

[8]Ed Note: Subbase referred to is commonly called "pit run" or "subgrade reinforcement."

greatest thickness.

6. Check the geotextile strength requirements for survivability as will be discussed in Section 5.8.

7. Check the geotextile filtration characteristics on the basis of the gradation and permeability of the subgrade, the water table conditions and the retention and permeability criteria given in Chapter 2.

8. Follow installation procedures covered in Section 5.11.

Other design methods for improving the structural capacity of permanent roads using geotextiles (e.g., Hamilton and Pearce, 1981) and geogrids (e.g., Haas, 1986; Haas, et al., 1988) have been proposed. NCHRP research currently underway at the Georgia Institute of Technology is directed towards answering the remaining questions regarding geosynthetics in permanent roadways.

5.7 Design Example

See Addendum by GeoServices, Inc.[9]

5.8 Geotextile Survivability

The selection of the geotextile to be used for either permanent or temporary roads is basically the same. If the roadway system is designed correctly, then the stress at the level of the geotextile due to the weight of the aggregate and the traffic should be not greater than the bearing capacity of the soil, which is relatively low (maximum of 30 psi) for subgrades where geotextiles are used. However, the stresses applied to the subgrade and the geotextile during construction may be well in excess of those applied to the materials in service. Therefore, selection of the geotextile is usually governed by the anticipated construction stresses. This is the concept of geotextile survivability that the geotextile must survive the construction operations if it is to perform its intended function.

Table 5-2 relates the construction elements (i.e. equipment, aggregate characteristics, subgrade preparation and subgrade strength) to the severity of the loading imposed on the geotextile.

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[9]Ed Note: No design example included in this appendix.

TABLE 5-2

RELATIONSHIP OF CONSTRUCTION ELEMENTS TO SEVERITY OF LOADING IMPOSED ON GEOTEXTILE IN ROADWAY CONSTRUCTION

	SEVERITY CATEGORY		
VARIABLE	LOW	MODERATE	HIGH TO VERY HIGH
Equipment	Light weight dozer (8 psi)	Medium weight dozer; light wheeled equipment (8-40 psi)	Heavy weight dozer; loaded dump truck (>40 psi)
Subgrade Condition	Cleared	Partial cleared	Not cleared
Subgrade Strength (CBR)	<0.5	1-2	>3
Aggregate	Rounded sandy gravel	Coarse angular gravel	Cobbles, blasted rock
Lift Thickness (in.)	18	12	6

If one or more of these items falls with a particular severity category (i.e., low, moderate, or high to very high), then geotextiles meeting these survivability requirements should be considered. However, some judgment is required in using these criteria. For example, if you were going to have a heavy weight dozer operating on a cleared but soft subgrade using coarse, angular aggregate fill in lifts of 12 inches, then a moderate to high survivability geotextile probably should be specified.

The strength of the geotextile required to survive the most severe conditions anticipated during construction can then be determined from Table 5-3 provided by Task Force 25. Geotextiles that meet or exceed the survivability requirements could thus be considered acceptable for the project. <u>It is important to realize that these survivability requirements were not based on any systematic research but on the properties of geotextiles which apparently have performed satisfactorily as separators in temporary roads and similar applications. There is currently some question as to the validity of the numbers with current research indicating that elongation may also be a factor. However, in the absence of any other information, they can be used as minimum interim values. The user is cautioned to use judgment and experience in selecting final specification values and should verify the geotextile survivability for major projects by conducting field tests under site specific conditions.</u>

These field tests would involve trial sections using several geotextile samples on a couple of typical subgrades at the site, and with different types of construction equipment. After construction, the samples would be exhumed and examined as to how well or how poorly they tolerated the imposed construction stresses. These tests could be done during design or after the contract was let, similarly to what is recommended for riprap placement (Section 3.8, Item 6e). In this case, the contractor is required to demonstrate that the proposed subgrade condition, equipment, and aggregate placement will not damage the geotextile. Then, if necessary, additional subgrade cleaning, increased lift thickness, and/or possibly different construction equipment could be utilized. In rare cases, the contractor may even have to supply a different geotextile.

The geotextile must also be selected so that it will retain the underlying subgrade and so that it will allow the underlying subgrade to freely drain. Thus, the geotextile must be checked using the drainage and filtration requirements discussed previously in Chapter 2 and as summarized in Table 5-4.

TABLE 5-3

GEOTEXTILE STRENGTH REQUIRED FOR
SURVIVABILITY DURING CONSTRUCTION

AASHTO-AGC-ARTBA JOINT COMMITTEE
(INTERIM SPECIFICATIONS)
MINIMUM[1] FABRIC PROPERTIES REQUIRED FOR FABRIC SURVIVABILITY[10]

Required Degree of Fabric Survivability	Grab Strength[2] (minimum values) (lbs)	Puncture Strength[3] (lbs)	Burst Strength[4] (psi)	Trap[5] Tear (lbs)
Very High	270	110	430	75
High	180	75	290	50
Moderate	130	40	210	40
Low	90	30	145	30

1 All values represent minimum average roll values (i.e., any roll in a lot should meet or exceed the minimum values in this table). Note: These values are normally 20% lower than manufacturer's reported typical values.

2 ASTM D-4632. Grab Method.

3 ASTM D-4833.

4 ASTM D-3787, Diaphragm Test Method.

5 ASTM D-4535, either principal direction.

[10]Ed Note: The values in Table 5.3 are similar to Table 720-1 in Forest Service Specifications for Construction of Roads and Minor Drainage Structures, EM-7720-100R, 1985.

Table 5-3	Table 720-1
Very High	(C) Heavy Duty Stabilization
High	(B) Normal Stabilization
Moderate, Low	(A) Separation

TABLE 5-4

GEOTEXTILE DRAINAGE AND
FILTRATION REQUIREMENTS

I.	RETENTION	
	Wovens:[11]	$0_{95} \leq D_{85}$
	Nonwovens:	$0_{95} \leq 1.8\ D_{85}$
	For both:	$0_{95} \geq 0.3$ mm (U.S. No. 50 sieve)
II.	PERMEABILITY	
	$k_{geotextile} \geq k_{soil}$	
III.	CLOGGING	
	Filtration tests may be warranted in high water table situations. See Section 2.3.3.	

5.9 Cost Considerations

Once the decision has been made regarding the geotextile requirements, it is important that the minimum required properties be specified in detail so that substitution of fabrics with lower performance properties and lower cost will not occur. Fabric selection based on cost alone will not in most cases provide successful results.

Estimation of construction cost and benefit-cost ratios for geotextile-stabilized road construction is straight forward and basically the same as that required for reviewing alternative pavement designs. Primary factors include:

- The geotextile cost
- Cost of constructing the conventional design versus a geotextile design (i.e. stabilization requirements for conventional design versus geotextile design)

[11]Ed Note: 0_{95} is the opening size of the geotextile at which 95% of openings are smaller when measured with sand. D_{85} is the size of the soil particle where 85% of particles are smaller than this size.

- o stabilization aggregate requirements
- o over-excavation and replacement requirements
- o operational and technical feasibility
- o construction equipment and time requirements

o Cost of conventional maintenance during road service life versus improved service anticipated by using geotextile; estimated through pavement management programs.

o Regional past experience

Annual cost formulas such as the Baldock method (Illinois Department of Transportation, 1982) can be used, utilizing an appropriate present worth factor to obtain the present worth of future expenditures.

Cost tradeoffs should also be evaluated for different construction and fabric combinations. This would include subgrade preparation and equipment control versus geotextile survivability. In general, higher cost geotextiles with a higher survivability on the existing subgrade will be less expensive than the additional subgrade preparation cost necessary to use geotextiles with a lower survivability.

5.10 Specifications

Specifications should generally follow the guidelines in Section 1.6. The main considerations include of course the minimum geotextile requirements for design and those obtained from the survivability, retention and filtration requirements in Section 5.8, as well as the construction requirements covered in Section 5.11. As with other applications, it is very important for an engineer's representative to be on site during placement to observe that the correct geotextile has been delivered, that the specified construction sequence is being followed in detail, and that no damage to the geotextile is occurring. The following draft specification, slightly modified, from AASHTO-AGC-ARTBA Task Force 25 is an example.

AASHTO-AGC-ARTBA
TASK FORCE 25
SPECIFICATION GUIDE FOR GEOTEXTILES USED IN
SEPARATION AND FILTER APPLICATIONS
(DRAFT OF SEPTEMBER, 1987 WITH SLIGHT MODIFICATIONS)

1. Description

This work shall consist of furnishing, and placing a geotextile primarily for use as a separator and filter to prevent mixing of dissimilar materials such as subgrades and surfaced and unsurfaced pavement structures, zones in embankments, foundations and select fill materials. The geotextile shall be designed to allow passage of water while retaining in situ soil without clogging. This specification does not address reinforcement applications which require an engineered project specific design.

2. Materials

Fibers used in the manufacture of geotextile, and the threads used in joining geotextiles by sewing, shall consist of long chain synthetic polymers, composed of at least 85% by weight polyolefins, polyesters, or polyamides. Both the geotextile and threads shall be resistant to chemical attack, mildew and rot. These materials, based on construction survivability conditions defined in Table 5-2, shall conform to the physical requirements of Tables 5-3 and 5-4.

3. Construction Methods/Requirements

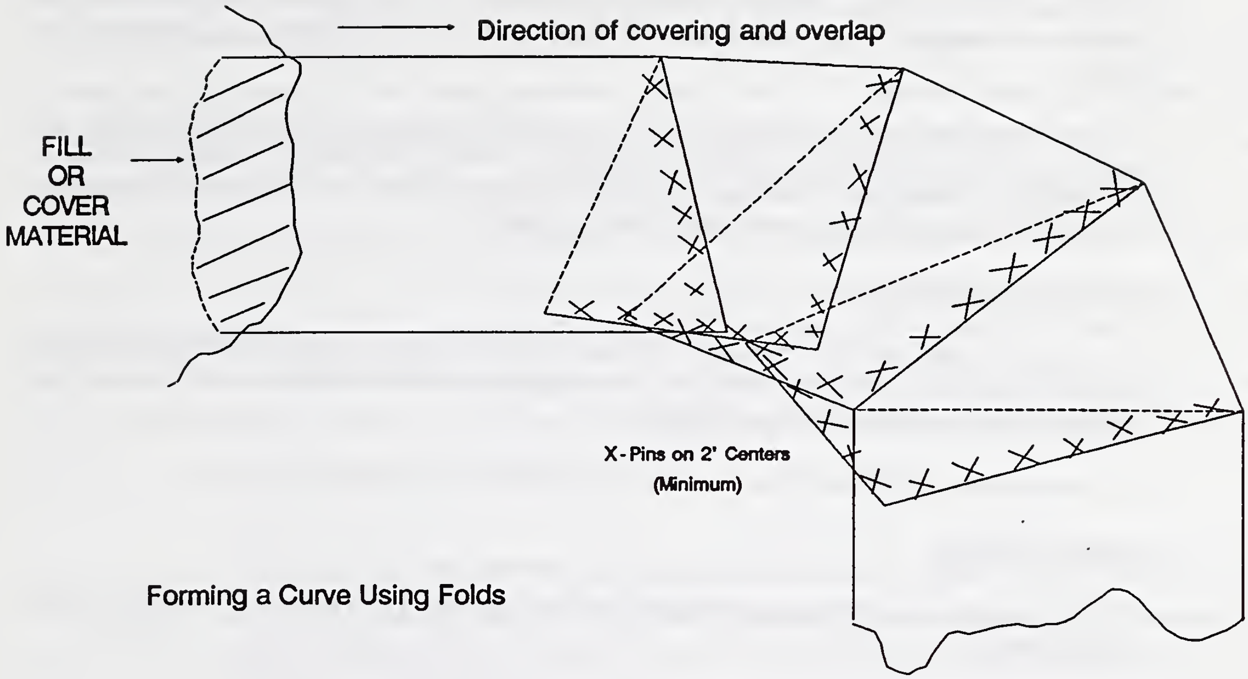
3.1 Geotextiles Packaging and Storing - Geotextile rolls shall be furnished with suitable wrapping for protection against moisture, and extended ultra-violet exposure prior to placement. Each roll shall be labeled or tagged to protect product identification sufficient for field identification as well as inventory and quality control purposes. Rolls shall be stored in a manner which protects them from the elements. If stored outdoors, they shall be elevated and protected with a waterproof cover.

3.2 Geotextile Exposure Following Placement - Exposure of geotextiles to the elements between lay down and cover shall be as soon as possible but not more than 3 days to minimize damage potential.

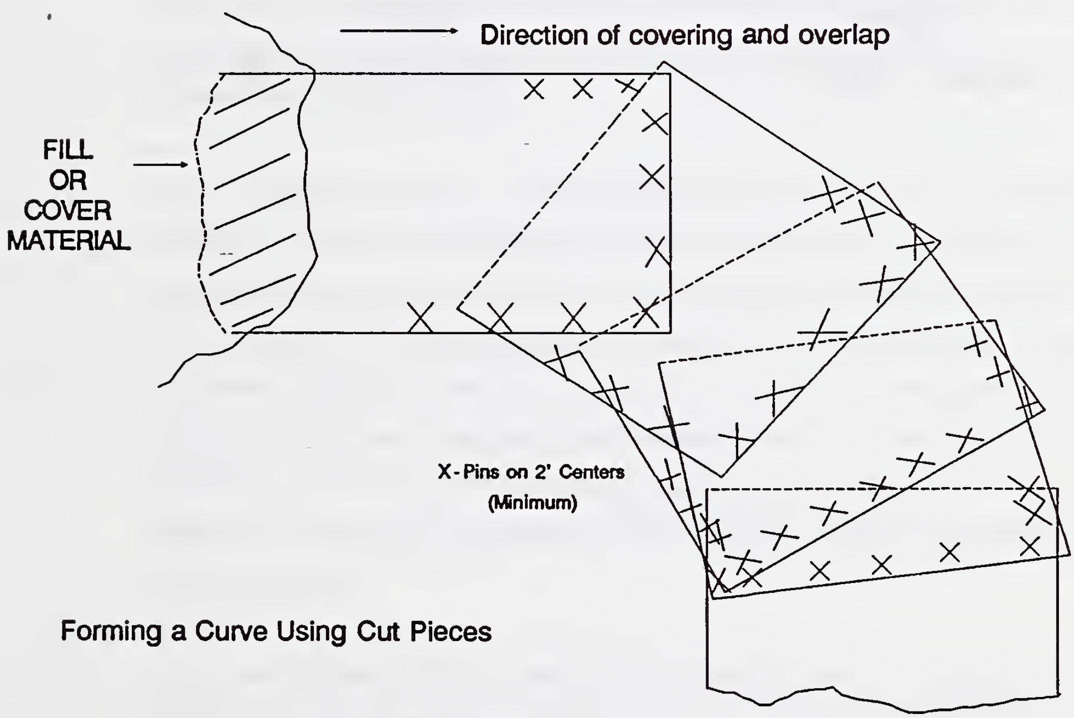
3.3 Site Preparation - The installation site shall be prepared by cleaning, grubbing, and excavation or filling to the design grade.

NOTE: Soft spots and unsuitable areas will be identified during site preparation or subsequent proof rolling. These areas shall be excavated and backfilled with select material compacted to normal procedures.

3.4 Installation - Geotextile installation shall proceed in the direction of construction. The geotextile shall be laid and overlapped in the direction as shown on the plans and shall be as wrinkle free as possible. On curves, the fabric may be folded or cut to accommodate the curve. As shown on Figure 5-17, the fold or overlap of cut pieces shall be in the direction of construction, and pinned, stapled or weighted with cover material. The minimum initial cover will comply with the plans and specifications or shall be selected with aid of Table 5-2. Placement and grading of fill, subbase, or base material shall proceed in the direction of construction. Ruts that occur in placed material during construction shall be filled with the appropriate material which should be subsequently compacted.



Forming a Curve Using Folds



Forming a Curve Using Cut Pieces

Figure 5.17 Forming Curves Using Geotextiles

3.5 Joints, Seams and Overlays - Where seams are required, they shall be joined by either sewing, sealing, or overlapping. All seams shall be subject to approval of the engineer. Both factory and field sewn or sealed seams shall conform to the requirements of Table 5-3. Optional, overlapped seams shall have a minimum overlap of 12 inches or as shown on the plans.

3.6 The contractor shall patch rips or tears in the geotextile as approved by the engineer (repairs shall be performed by placing a new layer of fabric extending beyond the defect in all directions a minimum of the overlay required for parallel rolls. Alternatively, the defective section shall be replaced as directed by the Engineer).

4. Method of Measurement

4.1 The geotextile shall be measured by the number of square yards computed from the payment lines shown on the plans or from payment lines established in writing by the Engineer. This excludes seam overlaps.

4.2 Excavation, backfill, bedding and cover materials are separate pay items.

5. Basis of Payment

5.1 The accepted quantities of geotextile shall be paid for at the contract unit price square yard in place.

5.2 Payment will be made under:

Pay Item	Pay Unit
Separator Geotextile	square yard

5.11 Installation Procedures

Successful use of geotextiles in roadways requires proper installation. Figure 5.18 shows the proper sequence of construction when using geotextiles. Even though the installation techniques appear fairly simple, a majority of the problems with geotextiles in roadways have occurred as the result of improper construction techniques. If the geotextile is ripped or punctured during construction activities, it will not likely perform as desired. If the geotextile is placed with a lot of wrinkles or folds, it will not be tensioned, and therefore will not provide any reinforcing effect. Other problems occur due to insufficient cover over fabric, rutting of the subgrade prior to placing the fabric, and placing lift thicknesses such that the bearing capacity of the soil is exceeded. The following step-by-step procedures should be followed, along with good engineering observations of all construction activities.

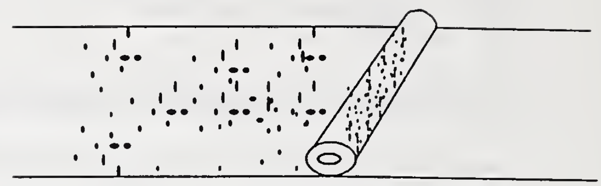
1. The site should be cleared, grubbed, and excavated to design grade, taking care to strip all topsoil, soft soils, or any other unsuitable materials (Figure 5.18a). If moderate site conditions exist, i.e., CBR greater than 1, lightweight proofrolling operations should be considered to aid in locating unsuitable materials to be removed. Isolated pockets where over-excavation is required should be pitched and backfilled so as to promote positive drainage. Optionally, special drain tiles with outlets installed to drain these isolated areas could be used.

2. During stripping operations, care should be taken not to disturb the subgrade. This may require the use of lightweight dozers or grade-alls for low strength, saturated noncohesive and low cohesive soils. For extremely soft ground, such as peat bog areas, consideration should be given to not over-excavate the surface materials such that advantage can be taken of the root mat, if it exists. In this case, all vegetation should be cut off square at the ground surface. Sawdust or sand can be placed over stumps or roots that extend above the ground surface to cushion the geotextile. Remember, the subgrade preparation must correspond to the survivability properties of the geotextile.

3. Once the subgrade along a particular segment of the road alignment has been prepared, the geotextile should be rolled in line with the placement of the new roadway aggregate (Figure 5.18b). Field operations can be expedited if the geotextile is pre-sewn in the factory to design widths such that it can be unrolled in one continuous sheet. The geotextile should not be dragged across the subgrade. The

a.

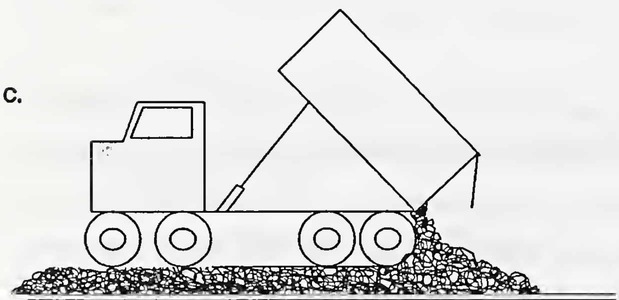
b.



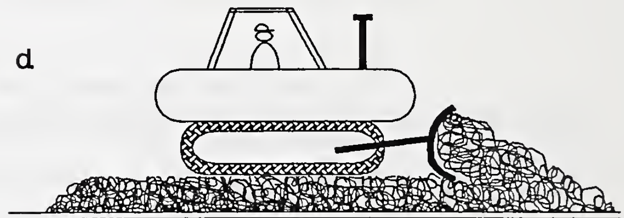
1. Prepare the ground by removing stumps, boulders, etc,; Fill in low spots.

2. Unroll the geotextile directly over the ground to be stabilized. If more than one roll width is required, overlap rolls. Inspect geotextile.

c.



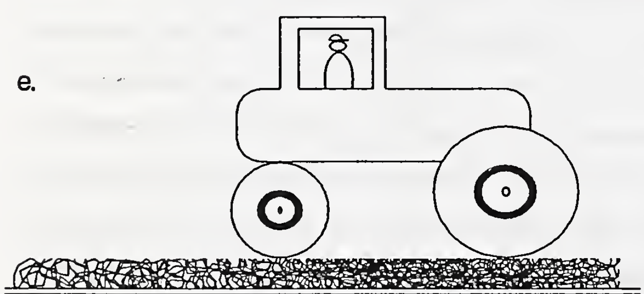
d.



3. Back dump aggregate onto previously placed aggregate. Do not drive directly on the geotextiile. Maintain at least 6" to 1' cover between truck tires and geotextile.[11]

4. Spread the aggregate over the geotextile to the design thickness.

e.



5. Compact the aggregate using dozer tracks or vibratory roller.[12, 13]

11. Ed Note: For temporary roads, the entire depth of aggregate, determined using figures 5.2 to 5.16, must be placed before loaded trucks are driven across aggregate.

12. Ed Note: Use extreme caution using vibrating mode over wet subgrades.

13. Ed Note: Adjust final depth in the field (2 to 3 inch increments) during construction if rutting greater than 2 to 4 inches occurs under a few passes of haul trucks, after aggregate is spread and compacted.

Figure 5.18 Construction Sequence Using Geotextiles

entire roll should be placed and rolled out as smoothly as possible. Wrinkles and folds in the fabric should be removed by stretching and staking as required.

4. Parallel rolls of geotextiles should be overlapped, sewn or tied as required. Specific requirements are reviewed in detail later in the section.

5. For curves, the geotextile should be folded or cut and overlapped in the direction of the turn (previous fabric on top) (Figure 5.17). Folds in the geotextile should be stapled or pinned 5 feet on center.

6. When geotextile intersects an existing pavement area, the fabric should extend to the edge of the old system. For widening or intersecting existing roads where fabric has been used, consideration should be given to anchoring the fabric at the roadway edge. Ideally, the edge of the roadway should be excavated down to the existing fabric and the existing fabric sewn to the new fabric. Overlaps, staples, and pins could also be utilized.

7. Before covering, the condition of the geotextile should be observed by a qualified inspector experienced in the use of these materials to determine that no holes, rips, tears, etc., have occurred in the fabric. If any defects are observed, the section of the fabric containing the defect should be repaired by placing a new layer of fabric extending beyond the defect in all directions a minimum of the overlap required for parallel rolls. Alternatively, the defective section can be replaced.

8. The subbase aggregate should be end-dumped on the fabric from the edges of the fabric or on the previously placed aggregate (Figure 5.18c). For very soft subgrades, pile heights should be limited to prevent possible subgrade failure. The maximum placement lift thickness for such soils should not exceed the design thickness of the road.

9. The first lift of aggregate should be spread and graded down to 12 inches or to the design thickness if less than 12 inches prior to compaction (Figure 5.18d). At no time should equipment be allowed on the road with less than 8 inches (6 inches for CBR ≥ 2) of compacted aggregate over the fabric. For extremely soft soils, lightweight construction vehicles will likely be required for access on the first lift. Construction vehicles should be limited in size and weight such that rutting in the initial lift is no

greater than 3 inches. If rut depths exceed 3 inches, it will be necessary to decrease the size and/or weight of the construction vehicles or to increase the lift thickness. For example, it may be necessary to reduce the size of the dozer required to blade out the fill or possibly to deliver the fill in half-loaded rather than fully loaded trucks.

10. The first lift of subbase aggregate should be compacted by "tracking" with the dozer and then compacted with a smooth-drum vibratory roller to obtain a minimum compacted density (Figure 5.18e). For very soft soils, design density should not be anticipated for the first lift and in this case, compaction requirements should be reduced. One possible recommendation would be to allow compaction of 5% less than the required specification density.

11. Construction should be performed parallel to the road alignment. Turning should not be permitted on the first lift of subbase aggregate. Turn-outs may be constructed at the road edge to facilitate construction.

12. If the geotextile is to provide some reinforcing, pretensioning of the fabric should be considered. For pretensioning, the area should be proof-rolled by a heavily loaded rubber-tired vehicle such as a loaded dump truck. The wheel load should be equivalent to the maximum expected for the site. The vehicle should make at least four passes over the first lift in each area of the site. Alternatively, once the design aggregate has been placed, the roadway could be used for a time prior to paving such that prestressing the fabric in key areas could be obtained.

13. Any ruts that form during construction should be filled in as shown on Figure 5.19 to maintain adequate cover over the fabric. In no case should ruts be bladed down as this would decrease the amount of aggregate cover between the ruts.

14. All remaining subbase aggregate should be placed in lifts not exceeding 9 inches in loose thickness and compacted to the appropriate specification density.

5.11.1 Overlaps

Overlaps can be used to provide continuity between adjacent geotextile rolls, through frictional resistance between the overlaps. Also, a sufficient overlap is required to prevent soil from squeezing into the aggregate at the fabric joint. The amount of overlap depends primarily on the soil conditions

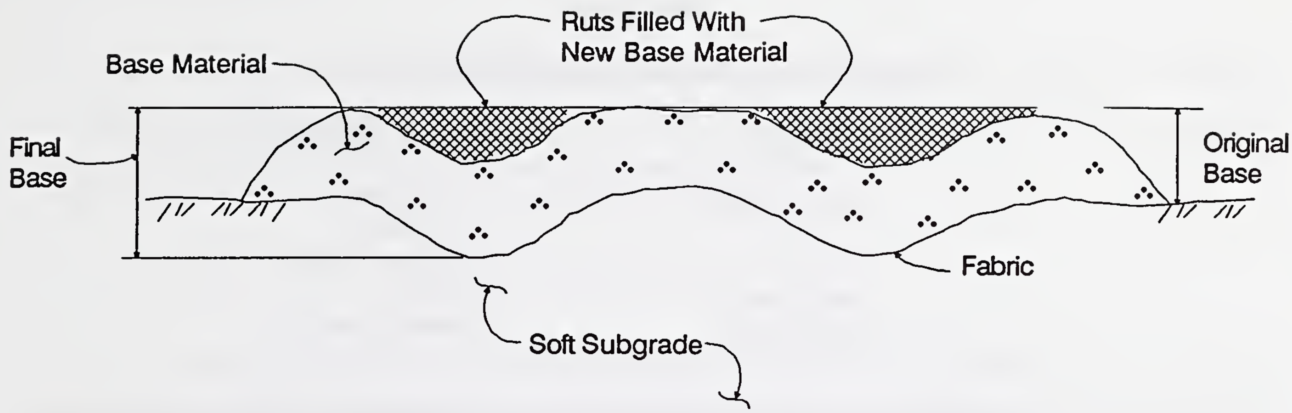


Figure 5.19 Repair of Rutting with Additional Base Material

and the potential for equipment to rut the soil. If the subgrade will not rut under construction activities, only a minimum overlap sufficient to provide some pullout resistance is required. As the potential for rutting and squeezing of soil increases, the required overlap increases. Since rutting potential can be related to CBR, it can be used as a guideline for the minimum overlap required, as shown in Table 5-5.

TABLE 5-5

Recommended Minimum Overlap Requirements

CBR	Minimum Overlap
Greater than 2	1 - 1.5 feet
1 - 2	2 - 3 feet
0.5 - 1	3 feet or sewn
Less than 0.5	Sewn
All roll ends	3 feet or sewn

The geotextile can be stapled or pinned at the overlaps to maintain them during construction activities. Ten to twelve inch long nails should be placed at a minimum of 50 feet on centers for parallel rolls and 5 feet on centers for roll ends.

Fabric widths should be selected such that overlaps of parallel rolls occur at the center line and at the shoulder. Overlaps should not be placed along anticipated main wheel path locations.

Overlaps at the end of rolls should be in the direction of the aggregate placement (previous roll on top).

5.11.2 Seams

When seams are required for separation applications, it is recommended that the seams meet the same tensile strength requirements for survivability as required for the geotextile, Table 5-3 in the direction perpendicular to the seam (as determined by the same testing methods). (Seaming IS discussed in detail in Chapter 1). All factory or field seams should be sewn with thread having the same or greater durability and strength as the material in the fabric. "J-seams" with interlocking stitches are recommended. Alternatively, if bag-type stitches, which can unravel, or butt-type seams are used, seams should be double-sewn with parallel stitching spaced no more than 1/4 to 1/2 inch apart. Double sewing is required to provide a safety factor against undetected missed stitches. The strength of the geotextile may actually have to be greater than specified, in order to provide seam

strengths equal to the specified tensile strength.

For certain types of geotextiles, such as nets, webs, and grids, tying or interlocking with wire cables, plastic pipe, etc. may be required. Consult the manufacturer.

5.12 Field Inspection

The field inspector should review the field inspection guidelines in Chapter 1, Section 1.7. Particular attention should be paid to the factors that affect geotextile survivability: subgrade condition, aggregate placement, lift thickness, and equipment operations.

5.13 Selection Considerations

For the geotextile to perform its intended function as a separator in roadways, it must be able to tolerate the stresses imposed on it during construction; i.e., the geotextile must have sufficient survivability to survive the anticipated construction operations. Geotextile selection for roadways is usually controlled by survivability and the guidelines given in Section 5.8 are most important in this regard. As mentioned, the specific geotextile property values given in Table 5-3 have been questioned and are subject to revision. In the meantime, for important projects, you are strongly encouraged to conduct your own field trials, as described in Section 5.8.